DOCTOR OF PHILOSOPHY

Topographic and material controls on the Scottish debris flow geohazard

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University of Dundee

Topographic and Material Controls on the Scottish Debris Flow Geohazard

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Declaration

This is to certify that neither this thesis, nor any part of it, has been presented or is currently submitted in candidature for any degree at any other university.

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Certification of Research

This is to certify that, except where specific reference to other investigation is made, the work described in this thesis is the result of the investigation of the candidate.

	F. D. Milne Candidate

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Abstract

Debris flows can be considered the most significant geological hazard in areas of high relief in Scotland having impacted upon slope foot infrastructure several times in recent years. The potency of this geohazard is anticipated to increase over the coming decades due to a climatologically enforced upturn in debris flow frequency. In this research material and topographic controls on debris flow activity are investigated using a combination of field and laboratory based analysis of debris flows at six study sites across upland Scotland. Centrifuge modelling is also used to simulate the initiation of debris flows in soils with varying particle size distributions.

Spatial densities of debris flow measured in the field indicate that hillslopes underlain by sandstone and granitic bedrocks, which tend to be mantled by coarser sand rich soils, have a greater frequency of flows than those underlain by schist and extrusive lava bedrocks. Higher debris flow densities on slopes underlain by sandstone and granite lithologies are facilitated by high permeability in overlying regolith matrixes allowing pore water pressures to increase more rapidly during rainstorms although this is likely to be further influenced by packing and organic content. Centrifuge modelling of hillslope debris flows also demonstrate that sandier soils are generally geotechnically more susceptible to slope failure.

The susceptibility of a hillslope to debris flow is strongly influenced by slope geometry and morphology. Hillslopes with persistently steep slopes and a high incidence of concavities, gullies and couloirs are topographically more predisposed to debris flow activity due to greater shear stresses and morphologically controlled, gravity induced concentrations of hillslope hydrology. The majority of material in channelised debris flows is entrained during the gully propagation stage of the mass movement. Consequently, such events can be considered *accumulative channelised debris flows*. Longer and steeper gullies with greater sediment capacities are more likely to yield larger flow mass movements. Coupling between open hillslopes and bedrock gullies is shown to be an essential component for conceptualisation of the debris flow geohazard.

Due to the role they play in amplifying debris flow magnitude, hazard management should be focussed around bedrock gullies and stream channels. Highest hazard rankings should be assigned to slope foot infrastructure in proximity to gullied stream channels with high sediment capacities and long, steep profiles conducive to large accumulative channelised debris flows. To avoid detrimental aesthetic impact, hazard management should be strongly geared towards utilisation of lower impact exposure reduction techniques and less visually intrusive engineering approaches such as increasing culvert capacity to accommodate debris flows. During realignment or the planning of future transport infrastructure, culverts with capacities significantly exceeding those required for purely hydrodynamic considerations should be placed straight on to stream channels avoiding proximal gully bends.

Keywords: Debris flow, geohazard, material controls, topographic controls, hazard management.

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1. Introduction

1.1 Background

A debris flow is a type of mass movement that involves the rapid downslope propagation of well graded granular solids mixed with water (Ballantyne, 2004a). The term is also used to describe the landform created by individual flows (Ballantyne & Harris, 1994). Debris flows represent the dominant process of mass movement on many steep slopes and occur widely across upland Scotland (Innes, 1983a) though the size of individual flows are generally much smaller than those in Scandinavian and alpine mountains (Innes 1985; van Steijn, 1996). Although the majority of Scottish debris flows occur in remote areas they have impacted upon slope foot infrastructure several times in recent decades presenting a risk to life and creating significant socio-economic impacts associated with disruption to the railway and road networks (Common, 1954; Jenkins *et al*. 1988; Ballantyne, 2002a; Winter *et al*. 2006; Nettleton *et al*. 2006). Consequently, debris flows can be considered the most significant geological hazard in areas of high relief in Scotland.

The primary triggering factor for debris flow generation is high magnitude rainfall which leads to soil saturation, reduced effective stress and thus slope instability. The importance of rainfall as a trigger for debris flow activity is highlighted by the fact that every recorded debris flow event in Scotland has coincided with intense or long duration rainstorms (Common, 1954; Baird & Lewis, 1957; Jenkins *et al*. 1988; Luckman, 1992; Ballantyne, 2002a; Winter *et al*. 2006; Nettleton *et al*. 2006). It is anticipated that future climate change will be characterised by increased occurrences in such high magnitude rainfall related to a more vigorous hydrological cycle caused by warmer global temperatures and a higher energy atmosphere (Conway, 1998). This upturn in the occurrence of debris flow generating, high magnitude rainstorms is likely to lead to a climatically induced increased frequency of hazardous debris flow events over the coming decades (Milne & Davies, 2007; Winter *et al*. 2007).

A complex and variable suite of contributory factors determine the susceptibility of any given hillslope to debris flow. However, material properties such as particle size distribution, permeability and frictional strength and geometric properties such as slope gradient and shape can be considered as key and universal controls on the propensity to debris flow. For example, it is widely acknowledged that slope gradients in excess of 25º are normally a prerequisite factor for debris flow occurrence and previous research has indicated that slopes underlain by coarse grained granite and sandstone lithologies and thus mantled by coarser, sandier matrixes tend to support a higher spatial frequency of debris flow (Ballantyne, 1981, 2002, 2004; Curry 2000a; Innes, 1982).

The risk presented to slope foot infrastructure in many areas of high relief in Scotland from debris flows coupled with an anticipated climatologically driven near future increase in the potency of the geohazard emphasize the necessity to understand as much as possible about the controls on hillslope susceptibility to debris flow activity in order to enable optimal conceptualisation and management of the debris flow geohazard.

1.2 Research Objectives

The primary aim of this research is to investigate the material and topographic controls on debris flow activity with a view to increasing our understanding of the debris flow geohazard in Scotland. To achieve this debris flow activity is examined at six study sites using a combination of laboratory and field based analysis. Centrifuge modelling is also used to simulate the initiation of debris flows in soils with varying particle size distributions. The primary aim of the research can be subdivided into the following component objectives:

- To investigate material and topographic controls on hillslope susceptibility to debris flow.
- Comment on material and topographic controls on debris flow magnitude.
- Observe the effect of rising pore water pressures in model soils with varying compositions in geotechnical centrifuge tests
- Comment on the implications of research findings for the management of the debris flow geohazard and offer suggestions for effective hazard mitigation.

It is envisaged that the research will further understanding of the debris flow process in Scotland and assist the management of the debris flow process during a period of climatically induced increase in the potency of the debris flow geohazard. It is also hoped that the work will have wider applicability to the management of the debris flow geohazard in other mountainous regions.

1.3 Layout of the Thesis

The thesis is presented in 10 chapters:

Chapter 2 reviews the current state of understanding surrounding the debris flow process. Issues arising from the literature review requiring further analysis and the wider significance of this research project are highlighted in this chapter.

Chapter 3 introduces the six study sites which this research revolves around. The location and physical characteristics of each site are outlined.

Chapter 4 details the methodology used in the research encompassing field and laboratory investigations and centrifuge modelling.

Chapter 5 describes field observations and measurements made at each of the study sites.

Chapter 6 gives results of laboratory investigations on sampled regolith from source areas of investigated debris flows.

Chapter 7 describes the rational and development of the centrifuge model. The apparatus and test procedures are also outlined and the results of tests are described.

Chapter 8 involves detailed interpretation of results from field, laboratory and model based investigations into topographic and material controls on the debris flow process.

Chapter 9 considers the implications of the research findings on the management of the Scottish debris flow geohazard. This involves consideration of how the research findings may be used to inform hazard assessment and assist implementation of effective hazard mitigation. The suitability of possible mitigative approaches is also addressed.

Chapter 10 describes the main findings of the research, summarises recommendations for debris flow hazard management and outlines suggestions for future work.

2. Debris Flow: Process, Trends and Geohazard

Before a detailed investigation into the material and geometric controls on the Scottish debris flow geohazard is carried out, it is important to obtain a wide understanding of the debris flow process and in particular the factors that determine susceptibility to debris flow mass movements. In this chapter a detailed overview of the debris flow process is given with particular reference to debris flow activity in Scotland. Spatial and temporal trends are also considered with a view to outlining general controls on debris flow distribution and causation. Finally, hazardous Scottish debris flows are reviewed and interpretations are made on the influence of anticipated climatic change on the debris flow process.

2.1 Debris Flow Terminology and Mechanisms

Debris flows in Scotland can be subdivided into two simplified types of flow (Ballantyne, 2004a). These are *hillslope flows* which occur on open, topographically unconfined slopes, and *channelised flows* which are contained for at least part of their length within a stream channel or bedrock gully (Brunsden, 1979; Ballantyne & Harris, 1994; Ballantyne 2004a) (figure 2.1 & 2.2). The division between the two types of flow is not clearly defined as hillslope flows are often partially confined in shallow gullies eroded into the slope material (Ballantyne & Harris, 1994; Ballantyne, 2004a) and hillslope flows can pass into bedrock gullies and continue downslope as channelised flows (Winter *et al*. 2006). Channelised debris flows also commonly emerge onto and spread across open ground towards the slope foot (Ballantyne, 2004a). A debris flow can be divided into three parts for examination of the intricacies of the debris flow process: the source area, the debris track and the debris deposits (figure 2.1).

Debris flows in Scotland are typically initiated on open hillslopes or gully walls as shallow translational landslides which rapidly make the transition from a sliding to a flow mass movement (Iverson, 1997; Ballantyne, 2004a). However, debris flows can also be triggered within stream channels as a result of the mobilisation of sediment on gully floors during flood torrents or due to the failure of debris dams (van Steijn *et al*. 1988; Bovis & Dagg 1992; Ballantyne, 2004a). Initiation of shallow translational sliding usually occurs as a result of a meteorologically induced increase in the phreatic surface leading to increased pore water pressures, reduced effective stress and thus slope instability (Summerfield, 1991; Selby, 1993; Ballantyne & Harris, 1994). During high intensity rainstorms slope failure can also be initiated as a consequence of the downward migration of a wetting front through granular materials, leading to failure at a shallow depth in the soil due to dissipation of soil suctions (Fourie, 1996; Springman *et al*. 2003; Wheeler *et al*. 2003).

Several researchers have cited critical state theory (Casagrande, 1936) in order to explain the phenomena of debris flow mobilisation from shallow landslides (Sassa, 1984; Iverson *et al*. 2000; Gabet & Mudd, 2006). Drained soil when continually sheared will eventually reach critical state porosity. To achieve critical state porosity loose soils contract whereas dense soils dilate (Casagrande, 1936; Gabet & Mudd, 2006). In large scale flume tests, Iverson *et al*. (2000) observed that shearing of a loose loamy sand resulted in instantaneous liquefaction due to rapid pore pressure increases generated by the transfer of the soil weight to the pore water during contraction. Conversely, experiments on the same soil in a densely packed state showed dilative behaviour on shearing which hindered mobilisation due to consequential pore pressure reduction (Iverson *et al*. 2000; Gabet & Mudd, 2006). However, as debris flows have been known to occur in dilative hillslope material (Anderson & Sitar, 1995; Gabet & Mudd, 2006) a mechanism must exist in which a dilative soil can attain contractive properties to become susceptible to liquefaction and debris flow (Gabet & Mudd, 2006). During slope failure in loose, compressive soils above the critical state porosity liquefaction occurs instantaneously (Iverson *et al*. 2000; Gabet & Mudd, 2006). Alternatively, where shallow translational landslides are initiated in dilative soils, the sliding slab initially remains largely intact but is subjected to bending, tensile cracking, remoulding and loss of structure as the mass moves over uneven ground (Selby, 1993). This results in a loosening of the soil which absorbs more water from intense rainfall and surface runoff causing further increases in pore pressures and compression during shearing which in turn leads to liquefaction and debris flow (Selby, 1993; Dai *et al*. 1999). The potential for debris flow mobilisation in dilative soils has been shown to be sensitive to particle size distribution with sandier soils more likely to liquefy than clay rich soils as a consequence of their greater permeability (Gabet & Mudd, 2006).

Following initiation and transition from sliding to flow mass movement, the debris flow propagates downslope developing a viscous fluid behaviour in which larger particles are typically transported upwards and pushed to the margins of the flow by higher surface velocities (Takahashi, 1981; Ballantyne & Harris, 1994, Ballantyne, 2002a, 2004a). Temporary damming of the mass movement can result from accumulations of boulders (and occasionally woody detritus) so that the flow becomes a multi-phase event characterised by a series of debris pulses (Ballantyne & Harris, 1994). It has been suggested that debris flow propagation in Scotland is typically characterised by a “cohesionless grainflow” whereby momentum is sustained by interparticle collisions (Innes, 1983b; Ballantyne & Harris, 1994; Ballantyne, 2004a). In this mechanism of flow movement it is suggested that larger debris are transported in a partially buoyant state within a finer matrix with a water content of between 10 and 30% (Blikra & Nemec, 1998; Ballantyne, 2004a).

The micro-relief of debris flows are often characterised by parallel levees of debris delimiting the track of the flow. These typically culminate in the formation of one or more terminal lobes of coarse clastic deposits towards the slope foot (Ballantyne & Harris, 1994) (figure 2.2). The morphology of debris flow deposits is largely determined by the water content and, consequently, the viscosity of the flowing mass (Blikra & Nemec, 1998). Debris flows with a high water content will propagate as low viscosity mass movements, commonly depositing broad terminal lobes or fans which spread out at the slope foot whereas flows with a low water content will display higher viscosity and will typically deposit elongate tongues or lobes of material (Ballantyne, 2004a). Higher viscosity flows also tend to deposit larger levees (Selby, 1993). Slopes that are susceptible to debris flow activity have often experienced extensive reworking of sediment in the past and consequently slope foot areas are widely mantled by deposits from previous debris flows (Curry, 2000a, 2000b). Repeated deposition of debris from successive channelised debris flows often form fan shaped accumulations of material at the slope foot known as debris cones (Brazier, 1987).

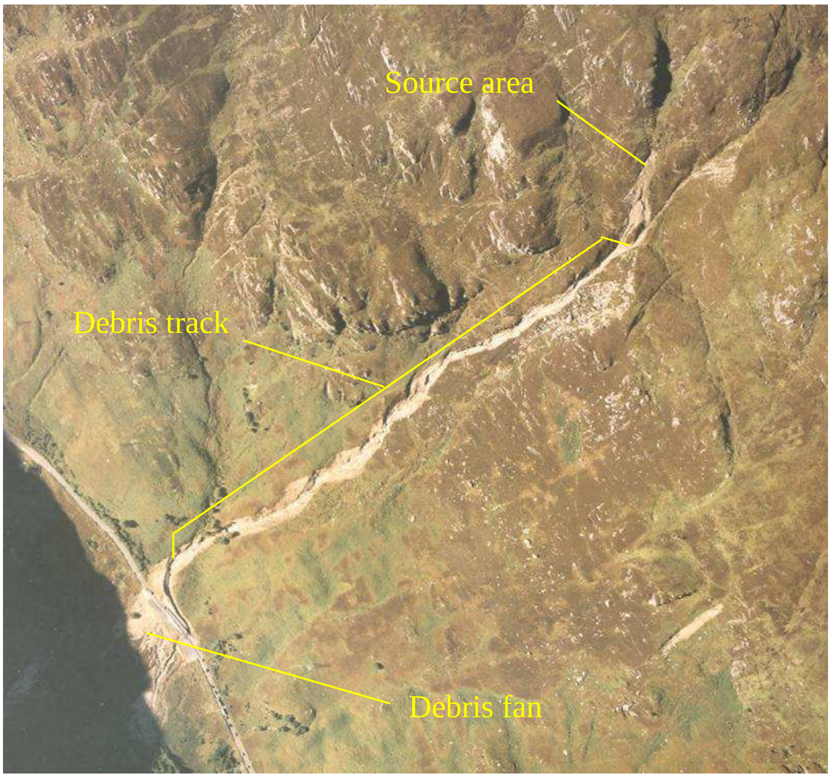


Figure 2.1: Aerial photograph of a channelised debris flow at Glen Ogle, Stirlingshire annotated to show the source area, debris track and debris flow deposits.

Figure 2.2: Hillslope debris flow in the Lairig Ghru, Cairngorm Mountains, Scotland, showing parallel debris flow levees and bouldery terminal lobes.

2.2 Triggering Factors

The primary trigger for debris flow activity around the world is high magnitude rainfall of high intensity and/or prolonged duration (Toll, 2001). The importance of rainfall as a trigger for debris flow activity is highlighted by the fact that every known recent Scottish debris flow event has coincided with high magnitude rainstorms both of high intensity and short duration and of low intensity and long duration formed under both cyclonic and anticyclonic synoptic conditions (Common, 1954; Baird &

Lewis, 1957; Jenkins *et al*. 1988; Luckman, 1992; Ballantyne, 2004a; Winter *et al*. 2006; Nettleton *et al*. 2006). Caine (1980) and Innes (1983b) attempted to quantify threshold values for rainstorm intensity and duration required for debris flow initiation. However, debris flow generation cannot be directly linked to rainstorm magnitude (intensity and duration) due to hydrogeological variability (Bardou & Delaloye, 2004) and the influence of antecedent soil moisture conditions (Church & Miles, 1987). The importance of antecedent soil moisture is demonstrated by the fact that in Scotland extensive debris flow landsliding has been known to occur as a consequence of 24 hour rainfall totals of 60 to 80 mm following wet weather, whilst much greater 24 hour rainfall totals of up to 140 mm following dry weather have failed to initiate widespread debris flow activity (Ballantyne, 2002a; 2004a). Consequently, it is widely accepted that the optimal conditions for debris flow generation occur when a high magnitude rainstorm follows a period of high antecedent rainfall (Winter *et al*. 2005).

Debris flow activity can also be initiated as a result of rapid snowmelt (Innes, 1983b; Ballantyne, 2004a; Winter *et al*. 2005). Snowmelt and snowmelt augmented with rainfall has been shown to be a significant debris flow generator in Iceland, accounting for 46% of recorded debris flows in the Northwest of the country (Decaulne & Saemundsson, 2003). Numerous debris flows triggered in the European Alps during the summers of 1987, 1999 and 2000 were also associated with snowmelt and rain-on-snow precipitation (Rickenmann & Zimmerman, 1993; Bardou *et al*. 2003) Those Alpine debris flows generated during the summer of 1987 occurred following a period of snowmelt which resulted in high antecedent soil moisture conditions which facilitated subsequent flow initiation by rainfall in July and August (Rickenmann & Zimmerman, 1993). In Scotland, snow cover in many areas of the highlands can lie for long periods of time. For example the 1971 – 2000 Spring average shows that snow can lie for up to 32 days in many areas of the Highlands (figure 2.3). Therefore, although all recorded debris flows in Scotland have occurred as a consequence of high magnitude rainstorms, it is likely that some of the debris flows present on Scottish hillslopes were triggered either directly as a result of rapid snowmelt leading to a rapid rise in pore water pressures, or indirectly due to heightened soil moisture conditions following snowmelt producing conditions conducive to subsequent rainfall induced debris flow activity.

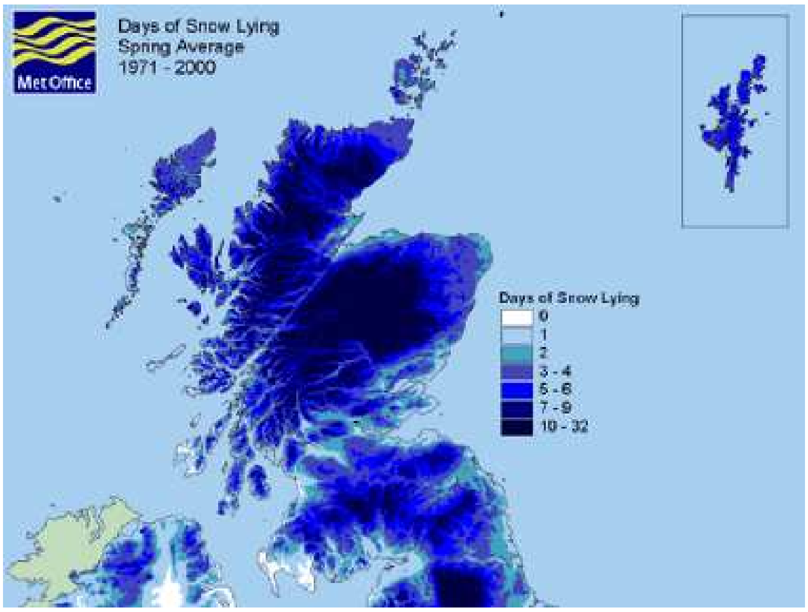


Figure 2.3: Days of lying snow in Scotland, spring average 1971 - 2000 (McMillan *et al*. 2005).

2.3 Contributory Factors

The susceptibility of any given hillslope to debris flow generation is determined by a complex and variable suite of contributory factors influencing the shear stress, the shear strength and the vulnerability of hillslope materials to hydro-meteorologically induced soil saturation. These can be broadly categorised as either topographic, material or biogenic/anthropogenic controls on debris flow occurrence.

2.3.1 Topographic controls

One of the most crucial topographic controls on susceptibility to debris flow generation is slope gradient. On steeper slopes hillslope material is subjected to higher shear stress and is therefore more susceptible to instability (Summerfield, 1991). Consequently, the gradient of debris flow source areas normally exceeds 30º (Brunsden, 1979; Ballantyne, 1981; Innes, 1983b) although debris flows can be triggered on slopes with lower angles. For example, Rapp and Nyberg (1981) observed debris flows in northern Scandinavia which had been initiated on slopes of 25.5º and debris flow initiation on gully floors can occur at gradients as low as 15-20º (Innes, 1983b). The maximum gradient for debris flow generation coincides with the threshold angle of stability above which regolith cannot accumulate. This is difficult to quantify as it is dependent on the properties of the slope material although an upper limit of debris flow initiation in the Scottish Highlands of between 45 and 50º has been suggested (Innes, 1983b; Heald & Parsons, 2005).

Topographic controls also strongly influence the hillslope hydrology with implications for debris flow initiation caused by morphologically driven localised increases in pore pressure and slope instability. For example, slopes with a convex profile may experience zones of tension at the crest leading to the formation of tension cracks which provide pathways for the rapid ingress of water into the slope material (Nettleton *et al*. 2005) whereas concave slopes may be subject to groundwater convergence towards the base of the profile (Wieczorek, 1987; Nettleton *et al*. 2005). Hillslope hollows and concavities often cause overland runoff and subsurface water flow to become concentrated during storms leading to localised slope instability (Reneau & Dietrich, 1987; Fannin & Rollerson, 1993; Palacios *et al*. 2003; Fernandes *et al*. 2004; Heald & Parsons, 2005). The presence of rocky outcrops and in particular hydrologic connectivity between chutes, couloirs and gullies and unconsolidated downslope material has also been shown to be a crucial control on the saturation of slope material and thus debris flow initiation (Luckman, 1992; Tarolli *et al*. 2008). The presence of upslope bedrock outcrops and cliffs can also provide a source of debris as a consequence of physical weathering leading to the accumulation of regolith. Therefore, areas corresponding with chutes and gullies in bedrock outcrops can be considered to be particularly prone to slope failure due to localised accumulations of hillslope material and topographically induced concentration of hillslope hydrology (Tarolli *et al*. 2008).

The presence of gullies and stream channels on hillslopes allow for the potential occurrence of channelised debris flows (Winter *et al*. 2005). During channelised flows material is entrained from the floors and walls of the gully. Consequently, channelised debris flows normally involve a larger volume of material compared to hillslope debris flows (Hungr *et al*. 1984; Fannin & Rollerson, 1993; Sterling & Slaymaker, 2007).

2.3.2 Material controls

Permeability and frictional strength are crucial material controls on slope stability. These are in turn determined by material properties such as particle size distribution, particle shape and unit weight. The frictional strength is influenced by the number of point contacts in a volume of a soil and the arrangement, size, shape and resistance to crushing of grains (Selby, 1993). When packing of particles is open and particles are of uniform size the points of contact are relatively few and strength is low whereas closer packing increases contact between grains thus increasing frictional strength. A wide range of particle sizes and more angular grain shapes also cause high soil strength (Craig, 2004). Grain size also has an important influence on water flow and pore water pressures within the slope material. Sediment permeability depends to a large extent on the size of the pore spaces through which water can flow. Therefore, water transmits much more freely through sands and gravels than through silts and clays. This results in a greater potential for rapid increases in pore pressures and consequential instability in slopes comprised of coarse grained sediment compared to slopes consisting of finer grained sediments.

The thickness of hillslope material is an important controlling factor on the occurrence of debris flow activity (Decaulne & Saemundsson, 2003; Palacios *et al*. 2003). The thicker the layer of material overlying the potential failure plane then the higher the normal stress acting on constituent particles, forcing them closer together and thus increasing the shear strength of the slope material. However, greater thickness of soil over potential slip planes also has the effect of increasing shear stress and thus the potential for instability (Summerfield, 1991). A sufficient thickness of material is also required to sustain debris flow activity. In Scotland this has been recognised as probably being in excess of 0.3 m depth of slope material (Innes, 1983b; Ballantyne, 1986). The thickness of slope material can also influence the timing and magnitude of channelised debris flow. Where debris flows pass through gullies cut into thick deposits of glacial till or talus, there is a greater potential for a higher frequency of high magnitude debris flows as there is a greater volume of material that can be mobilised during flow and there is greater recharge onto gully floors due to slumping and wash from thick deposits in gully walls (Bovis & Jakob, 1999; Jakob *et al*. 2005; Ballantyne, 2004b).

The parent rock from which the hillslope sediment is derived contributes substantially to the geotechnical properties of soil as it determines the mineralogical content and strongly influences particle sizes (Trenter, 1999). The importance of the control of the parent material on soil characteristics and therefore on hillslope susceptibility to debris flow has been demonstrated by observations that debris flows are more abundant on slopes mantled by regoliths with sandier, coarser grained matrixes yielded from coarse lithologies such as granite and sandstone compared to hillslopes underlain with finer grained schistose or extrusive igneous lithologies which commonly develop into soils with a larger silt component (Ballantyne, 1981, 1986, 2004a; Innes, 1983b; Curry, 2000a). Ballantyne (1986) suggested that this apparent increased vulnerability of coarser soils to flow generation is attributable to their higher permeability and consequential susceptibility to rapid increases in pore pressure during rainstorms.

As well as influencing the stability of the hillslope by determining the composition and textural characteristics of the soil matrix, the properties of the solid geology can influence the stability of a slope in several other ways. For example, if the underlying lithology is impermeable subsurface water will tend to flow along the interface between the soil and the bedrock potentially resulting in slope failure due to saturation and reduced effective stress (MacNaughton, 2004). The orientation of strata and the presence of unconformities and faults also exert a strong influence the distribution of springs which have been shown to facilitate the generation of debris flows (Heald & Parsons, 2005; MacNaughton, 2004). Furthermore, such structural zones of weakness typically facilitate localised preferential rock weathering, producing larger accumulations of regolith and thus a greater supply of sediment for debris flow activity compared to elsewhere on the hillslope (Nieuwenhuijzen & van Stein, 1990; Palacios *et al*. 2003; MacNaughton, 2004).

Alternatively, weathering processes affecting unconsolidated hillslope material such as freeze and thaw action in the winter and desiccation of soils (particularly organic soils) during dry conditions can gradually make slopes more susceptible to failure as a result of a deterioration in soil strength and provision of routes for rapid infiltration of surface water (through cracks in the soil) (Winter *et al*. 2005; Take, 2003; Take & Bolton, 2004). This process is known as preconditioning or slope ripening (Winter *et al*. 2005). The reduction of slope stability over time and changes in shear stress due to rainfall is represented graphically in figure 2.4. The development of fragipans (hardened mineral layers) such as iron pans (figure 2.5) within soil profiles may also lead to reductions in slope stability due to impeded percolation and the occurrence of heightened pore water pressures above the mineral layer (Brooks *et al*. 1995; MacNaughton, 2004). Failure may also be facilitated by a relatively low friction plane in conjunction with fragipans.

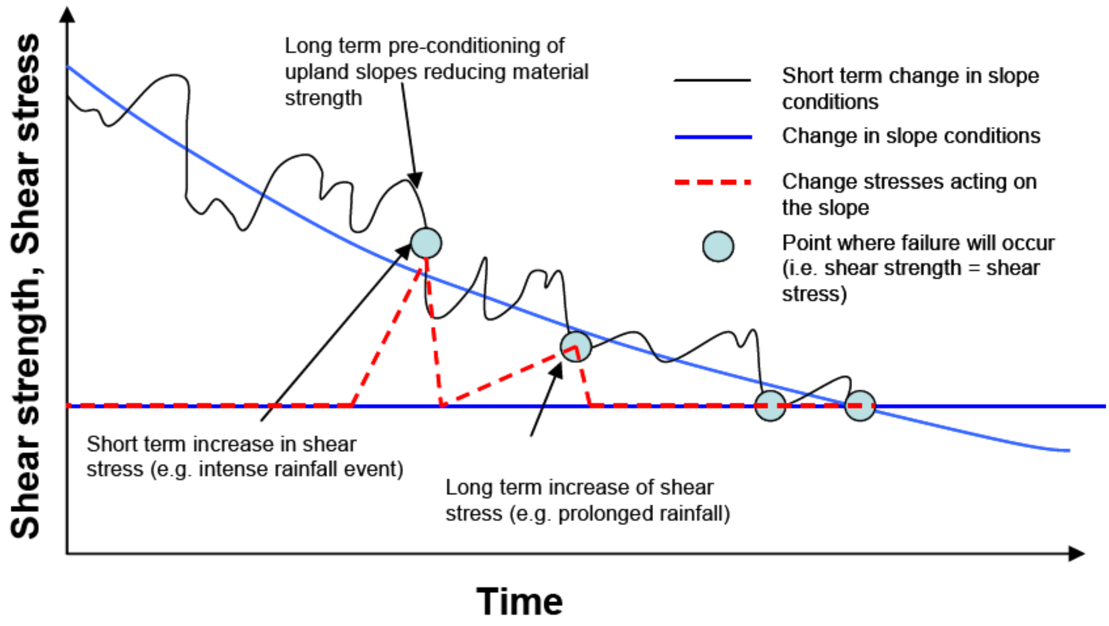


Figure 2.4: Long term development of upland slopes and their susceptibility to rapid landslides (Nettleton *et al*. 2005).

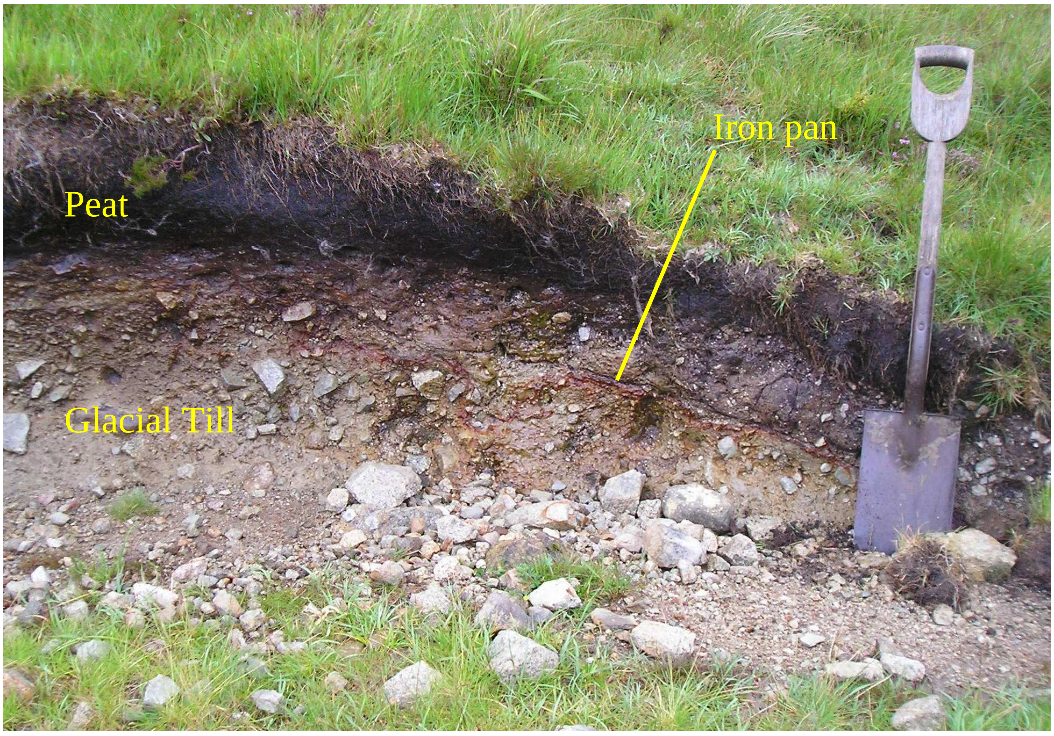


Figure 2.5: Iron pan (seen as dark red line parallel to ground surface) in exposed slope foot profile at Glamaig, Isle of Skye.

2.3.3 Biogenic and anthropogenic controls

Vegetation can play a critical role in stabilising hillslope material against failure on hillsides. Vegetation cover intercepts rainfall thus reducing infiltration of water into the soil. Vegetation also removes moisture from the slopes through the processes of evapotranspiration, increasing effective stress and consequently slope strength by reducing pore water pressures (Wilkinson *et al*. 2002). Root strength exerts an important contribution to slope stability by increasing frictional resistance to failure in thin soils where failure occurs in the rooting zone (Fannin & Rollerson, 1993; Selby, 1993; Mickovski *et al*. 2007; Sonnenberg *et al*. 2007; Sonnenberg, 2008). Based on several regional studies Buchanan and Savigny (1990) suggested values of root cohesion (c_r), the increase in apparent cohesion (c') from the mechanical support from roots in a soil, and classified them into 4 groups (table 2.1). The vast majority of Scottish hillslopes have grassland or heather vegetation cover and therefore fall into root cohesion group 1 where it is suggested that the mechanical support from roots in the soil ranges between 1.6 – 2.1 kPa. Although significantly lower than the root cohesion experienced in old forest growth, these values are still sufficient to exert a positive influence on slope stability (Buchanan and Savigny, 1990). Conversely, vegetation may have an adverse effect on slope stability if an increase in shear stress caused by loading from the weight of trees is not offset by soil reinforcement from the roots (Selby, 1993). Furthermore, while it is possible that roots may extend through the potential failure zone to the parent material thus anchoring the slope material, most vegetation in shallow soils has shallow root networks which stop short of the parent material leaving a plane of reduced strength immediately below the root zone along which failure could potentially take place (Selby, 1993; Brooks *et al*. 1995).

In populated mountain regions, shallow landsliding and debris flows can often result as a consequence of anthropogenic influences (Caine, 1980; Begueria, 2006). Removal of vegetation by deforestation and burning increases the possibility of debris flow activity by increasing water ingress into the soil as well as reducing root cohesion and evapotranspiration (Innes, 1983a; Bovis, 1993). Deforestation of hillslopes has resulted in widespread shallow translational landsliding in New Zealand, Alaska, British Columbia and Japan (Selby, 1993) and at the Drumochter Pass in the central Highlands of Scotland, debris flows were initiated in 1951 following the burning of dwarf shrub heath (Ballantyne, 2004a). Overgrazing by sheep has also been highlighted as a potential contributory factor to debris flow activity. For example, it has been suggested that the onset of gully erosion and enhanced debris flow activity in the Howgill Fells in northern England relate to human-induced vegetation change in the 10th century AD due to the introduction of Scandinavian sheep farming practices (Harvey *et al*. 1981).

Root Cohesion Group	**Root Cohesion (kPa)**	**Comments**
1	1.6 - 2.1	Understory vegetation (grasses, sedges, shrubs)
2	2.1 - 2.5	Scrub forest (understory vegetation with scrub trees)
3	2.5 - 3.0	Mixed forest (understory vegetation and healthy forest)
4	>3.0	Old growth forest

Table 2.1: Simplified root cohesion groups (after Buchanan & Savigny, 1990) (Fannin & Rollerson, 1993).

2.4 Hillslope Material

Matrixes in mountain soils are predominantly sand dominated with very low clay content with particle size distributions strongly determined by the characteristics of the parent material (Innes, 1986). Much of the hillslope material that is subjected to debris flow in Scotland has it genesis from the retreat of the last Scottish Ice Sheet during the Dimlington Stadial (*c*.26 ka – 13 ka BP) and the smaller scale glaciation during the Loch Lomond Stadial (*c*.11 ka – 10 ka BP) (Craig, 1991). At the height of the Dimlington Stadial approximately 18,500 years ago, Scotland was covered by an ice sheet up to 1.5 km thick from which only the highest mountain summits protruded to form nunattacks (figure 2.6a) (Stone *et al*. 1998). The later readvance of ice during the Loch Lomond Stadial was much smaller in extent than the Dimlington Stadial glaciation. At the zenith of the Loch Lomond Stadial glaciation, ice coverage was restricted to a large icefield covering much of the western Highlands with other smaller plateau ice caps, valley and corrie (cirque) glaciers existing in areas such as the south east Grampians and the Cairngorms (figure 2.6b) (Sissons, 1979a). Glacial drift in mountain environments tends to have a very localised provenance as sediments were largely derived from reworked pre-existing deposits and material supplied from exposed rockwalls to the surface and margins of the glacier (Trenter, 1999). During downwastage of the Dimlington Stadial ice sheet and during the Loch Lomond Stadial, hillslopes outwith the limits of the ice were subjected to intense periglacial activity resulting in the accumulation of regolith and aprons of talus which are prone to reworking by debris flow (Salt & Ballantyne, 1997; Hinchcliffe, 1999). Large areas of Scotland are covered in glaciofluvial deposits formed from the reworking of glacial material by melt water beneath, on top and within the ice during the retreat of glacial ice. These tend to form deposits of well graded sand and gravel up to 10m thick (Benn & Evans, 1997). This type of material has also been known to yield flow mass movement such as the hazardous debris flow event on the A9 trunk road near Dunkeld in Perthshire on the 11th of August 2005 (Winter *et al*. 2005).

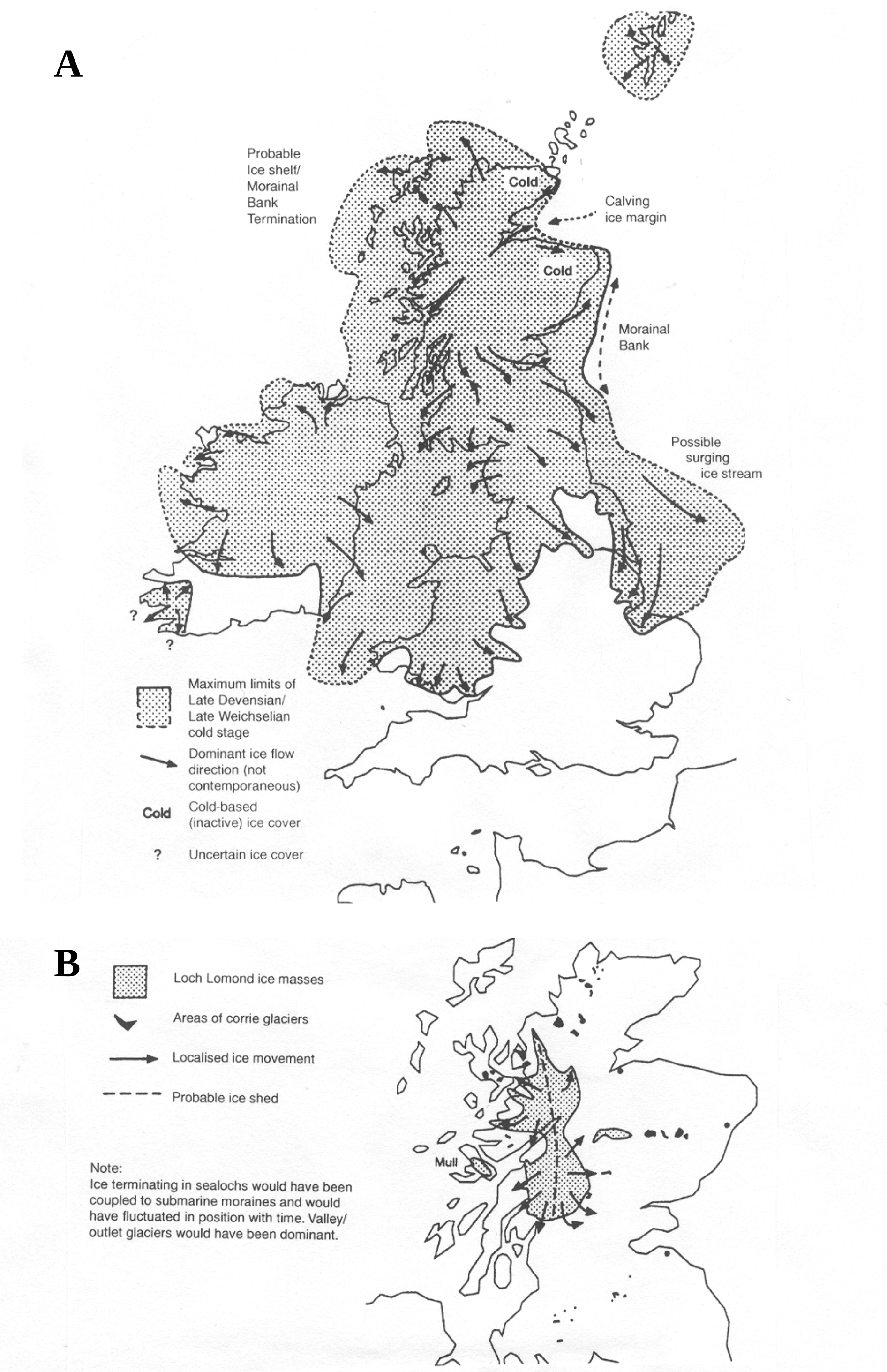


Figure 2.6: Maximum extent of ice coverage during (a) the Dimlington Stadial (c.26ka – 13ka BP) and (b) the Loch Lomond Stadial (c.11ka – 10ka BP) (Trenter, 1999).

2.5 Spatial and Temporal Trends

2.5.1 Spatial Trends

The distribution of debris flow activity in Scotland is strongly controlled by topography, lithology and the availability of sediment as determined by glacial erosion (Ballantyne, 1986). The potential for debris flows exists wherever the prerequisite factors of a suitable slope angle (usually in excess of 25° although the steepness of source areas in Scotland is rarely lower than 30-32º) and an adequate supply of slope material exists (Innes 1983a; Ballantyne, 1986). Accordingly, debris flows occur widely in areas of high relief in Scotland, representing the dominant agent of mass movement on many steep slopes (Ballantyne, 2004a). Innes (1983b) produced a map showing the main areas of debris flow activity in Scotland based on an aerial photo survey in which debris flow forms were identified within 100 km^2 grid squares (figure 2.7). Innes emphasised that the map under-represents the true distribution of debris flow in Scotland as some flows observed on the ground were not visible in the 1959 – 1962 photography used in the survey. Nevertheless, the map does highlight areas in Scotland where widespread debris flow activity is known to take place such as Skye, Glencoe, Lochaber and the Cairngorms as well as indicating an apparent absence of debris flows in other upland areas where debris flows are less frequent such as the south east Grampians and the Southern Uplands (Ballantyne, 2004a). The low spatial density of debris flows in such areas of high relief appears to be largely a function of the properties of hillslope materials determined by the underlying parent lithology (Ballantyne, 1986). Debris flows in Scotland are more prevalent on slopes mantled by regolith or drift with coarse grained, sandier matrixes developed over granites and sandstones compared to those mantled with slope material derived from schists, shales and extrusive lavas which tend to be characterised by finer grained, siltier matrixes (see section 2.3.2) (Ballantyne, 1981, 1986, 2004a; Innes 1982, 1983a). Some mountainous areas of Scotland exhibit a landscape that is the legacy of glacial scouring in which there is a lack of soil cover and bedrock is extensively exposed at the surface (Gordon, 1981). In these areas debris flow activity is restricted by a scarce supply of hillslope material of sufficient depth (Ballantyne, 1986).

It is also important to acknowledge that due to the importance of antecedent and high magnitude rainfall in generating mass movement, the potential for flow generation is greater in areas which experience higher rainfall totals. In Scotland the distribution of rainfall is heavily influenced by an orographically induced rainfall gradient characterised by higher rainfall totals in the west compared to eastern upland areas (figure 2.8). In conjunction with the landscape and material controls on spatial distribution rainfall patterns may also partially explain a higher frequency of debris flows in western areas such as Skye, Glencoe and Lochaber. Orographically influenced higher rainfall totals in the Cairngorms compared to surrounding upland areas are also conducive to a higher frequency of flow activity in that area.

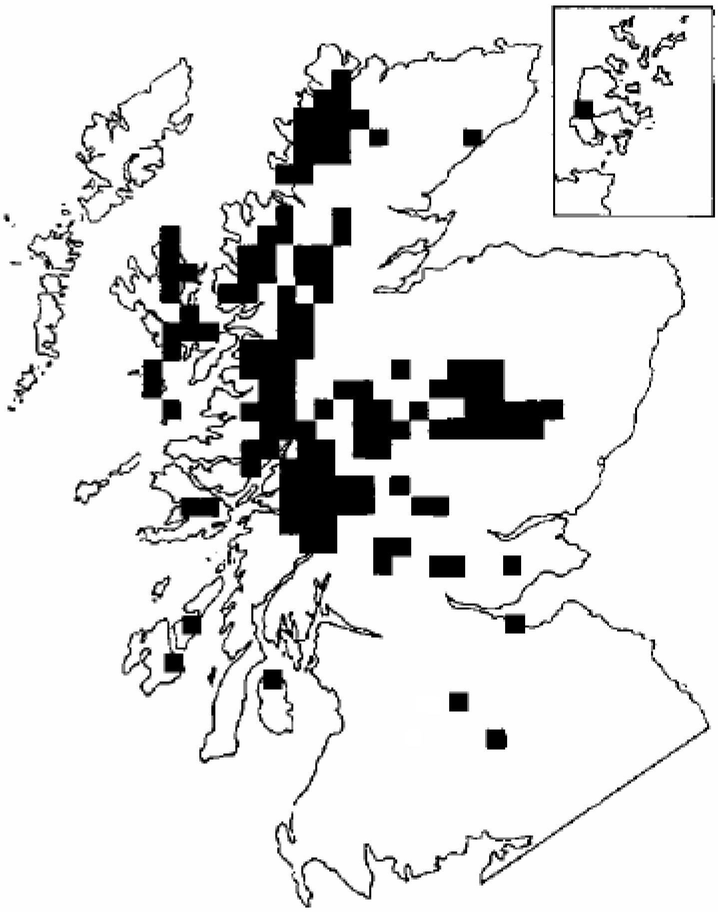


Figure 2.7: Spatial distribution of debris flow activity in Scotland (after Innes 1983a).

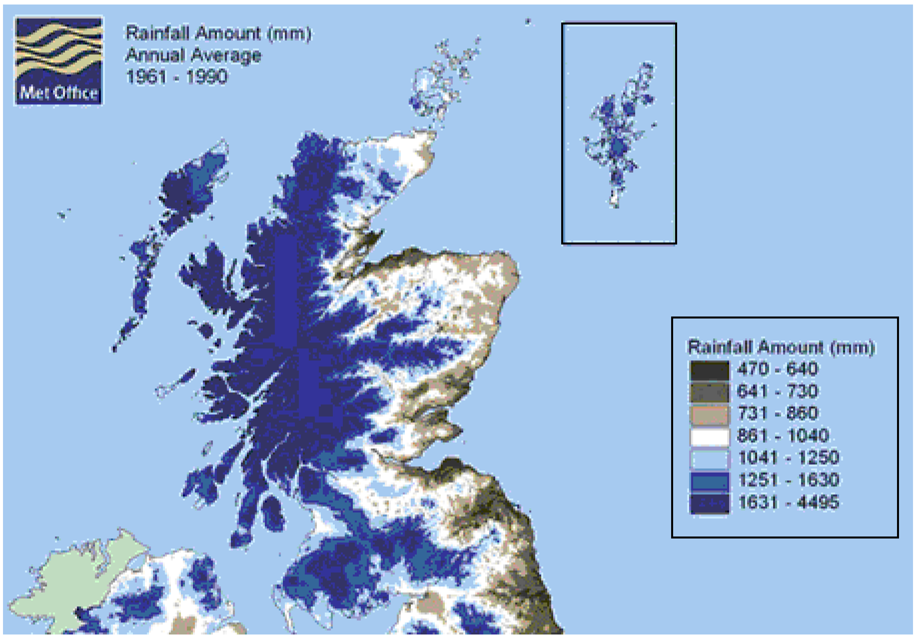


Figure 2.8: Average annual rainfall in mm across Scotland (1961-1990). Note the pronounced west to east rainfall gradient (Met Office, 2008).

2.5.2 Temporal Trends

Stratigraphic evidence suggests that debris flow activity was endemic in the Scottish Highlands following deglaciation at the end of the Dimlington and Loch Lomond Stadials (Benn, 1991, 1992; Bennett, 1999; Dix & Duck, 2000; Ballantyne, 2002a, 2002b, 2004a). Although the occurrence of this widespread paraglacial debris flow activity probably only lasted for a few hundred years (Ballantyne, 2004a) radiocarbon dating of debris flow deposits has provided evidence for the continued occurrence of sporadic debris flow over the past 7000 years (Hinchcliffe, 1998, 1999; Hinchcliffe *et al* 1998; Curry 2000a; Reid 2001; Ballantyne, 2004a). Data from the 9 studied sites around Scotland from which radiocarbon dates have been obtained suggest possible episodes of increased debris flow mass movement during the past 700 years, 1700–

2700 yrs BP, 3400-3800 yrs BP and 5900–6400 yrs BP with interludes of less frequent activity (figure 2.9) (Ballantyne, 2002a, 2004a). The dearth of radiocarbon dates from earlier than 7000 yrs BP is due to the absence of datable material sampled from the deepest parts of thick deposits and should not be interpreted as indicative of a hiatus in debris flow activity (Ballantyne, 2004a). Accordingly, it can be assumed that there has been continuous intermittent debris flow activity throughout the Holocene (*c*. 10 ka BP – present).

Lichenometric dating has been used to identify more recent temporal trends in Scottish debris flow activity by measuring *Rhizocarpon Geographicum* lichen diameters on flow deposits and calibrating the results using lichen growth rates measured on dated gravestones in local burial grounds (Innes, 1983a; Ballantyne, 2004a). This lichenometric data demonstrates that debris flow activity has occurred at the studied locations within most decades over the past 150-200 years (Innes, 1997) implying a "decadal or sub-decadal" recurrence interval (ranging from <10 to *c*. 40 years) at flow susceptible sites in the Scottish Highlands (Ballantyne, 2004a). Such recurrence intervals are consistent with those inferred from historical aerial photography and field observations over the past few decades (Common, 1954; Baird & Lewis, 1957; Innes, 1982; Luckman, 1992; Ballantyne, 2002a, 2004a). The recent temporal frequency of Scottish debris flows is broadly similar to that of flows in mountain areas of higher relief (Ballantyne, 2002a). For example, dendrochronological investigations of debris flow deposits in the French Alps (van Asch & van Steijn, 1991) and in the Rocky Mountains (Gardner, 1982) gave debris flow return periods of 4-45 years and 15-25 years respectively (Corominas *et al*. 1996; Ballantyne, 2002a). However, the current recurrence interval of Scottish debris flows cannot have been sustained throughout the Holocene as upper slope sediments would have been completely removed by debris flow activity within the first few centuries or millennia following the Late Glacial (Ballantyne & Benn, 1994; Curry 1999; Ballantyne, 2002a, 2002b, 2004a). Therefore, the endurance of largely intact upper slope sediment sources indicates that Scottish sites with a propensity to debris flow have experienced the current flow return period for no longer than a few hundred years at most (Ballantyne, 2002a, 2004a).

The apparent increased frequency of debris flow activity over the past few hundred years may have been caused by a reduction in the shear strength of hillslope material, an upturn in the frequency of high magnitude rainstorms, or by a combination of these factors (Ballantyne, 2002a). Over long periods of time, weathering of hillslope material can gradually decrease slope stability by altering the soil structure and reducing the frictional strength of soil (Winter, *et al*. 2005) Physically based hydrology-stability modelling of shallow translational landslides on podsol mantled Scottish hillslopes (Brooks *et al*. 1995) has indicated that progressive pedogenesis improves the ability of soil to maintain higher moisture content therefore increasing the likelihood of failure during subsequent rainstorms. Pedogenesis also gradually increases the thickness of soil over potential slip planes with the effect of progressively increasing shear stress and thus the potential for instability on hillslopes.

It has been suggested that human induced factors may have been responsible for a reduction in hillslope stability in recent centuries (Ballantyne, 2002a, 2004a). Innes (1982, 1983a) has proposed that muirburn (burning of dwarf shrub heath to improve grazing) may make slopes more vulnerable to mass movement through the destruction of the water-absorbing bryophyte basal layer leading to increased infiltration rates. The effect of overgrazing of hillslopes by sheep has also been highlighted as potentially being responsible for increased hillslope susceptibility to debris flow (Harvey *et al*. 1981; Innes, 1983a). Indeed, the effect of overgrazing was considered to have been the primary cause in the upturn in the incidence of debris flows affecting the road through Glen Coe in 1821 (Taylor, 1976). The road commissioners at the time reporting that “this sort of damage to the road and valley is said to be unknown, until the black cattle, formerly depastured thereabouts, were supplanted by sheep, whose habit of ranging on higher ground, disturbs and sets in motion the rocky rubbish of the summit…” (Taylor, 1976). However, it is important to acknowledge that this is non-scientific contemporary speculation and that the mentioned increase in debris flow activity may have been caused by another factor such as an upturn in the incidence of high magnitude rainfall or progressive pedogenisis.

Over the past few decades there appears to have been an increased occurrence of debris flows along the Scottish transport network (Winter *et al*. 2005). This may be associated with a contemporaneous increase in annual precipitation totals over the last few decades (Smith, 1995; Galbraith *et al*. 2005). Similarly, it has been suggested that periods of increased landslide activity earlier the Holocene may be attributable to higher rainfall totals associated with periods of increased storminess (Diez *et al*. 1996; Soldati *et al*. 2004). The possible influence of changing rainfall patterns on mass movement frequency are perhaps represented in the stratigraphy of a debris cone in Glen Feshie in the Cairngorm Mountains which exhibits a long period of inactivity between *c*. 2000 cal yr BP and 300-500 cal yr BP followed by the reoccurrence of sporadic flow activity and debris cone accretion (Brazier & Ballantyne, 1989). Brazier & Ballantyne (1989) hypothesised that recommencement of intermittent debris flow at the site was initiated by an extremely high magnitude rainstorm in the Little Ice Age (*c*. 500 – 100 yr BP) when Scotland was experiencing an upturn in both the frequency and intensity of cyclonic storms (Lamb, 1979, 1984; Whittington, 1985; Ballantyne & Harris, 1994; Ballantyne & Morrocco, 2006). It is suggested that erosion from the extreme rainstorm removed vegetative cover and exposed unconsolidated sediment in debris flow source areas resulting in a lower initiation threshold for subsequent mass movement events (Brazier & Ballantyne, 1989; Ballantyne & Harris, 1994; Ballantyne, 2002b). Therefore, if the proposed Glen Feshie mechanism is representative of slope destabilisation causal processes throughout Scotland, it indicates that enhanced debris flow activity over the past few centuries may have been initiated by extremely high magnitude rainstorms during the climatic deterioration of the Little Ice Age and continued by lower magnitude rainstorms to the present day.

Recent debris flows have been observed to have a seasonal temporal distribution in which the majority of debris flows occur either in the periods between July and August or November to January (Winter *et al*. 2005). This distribution of debris flow can be explained in terms of Scottish rainfall patterns. Rainfall data from western, central and eastern Scotland (figure 2.10) show that in July and August the weather is generally moving from drier conditions earlier in the summer towards wetter conditions, heralding a transition to higher soil moisture conditions more conducive to debris flow. The generally wetter conditions in the winter and the resultant high soil moisture conditions explain the increased occurrence of debris flows between November and January.

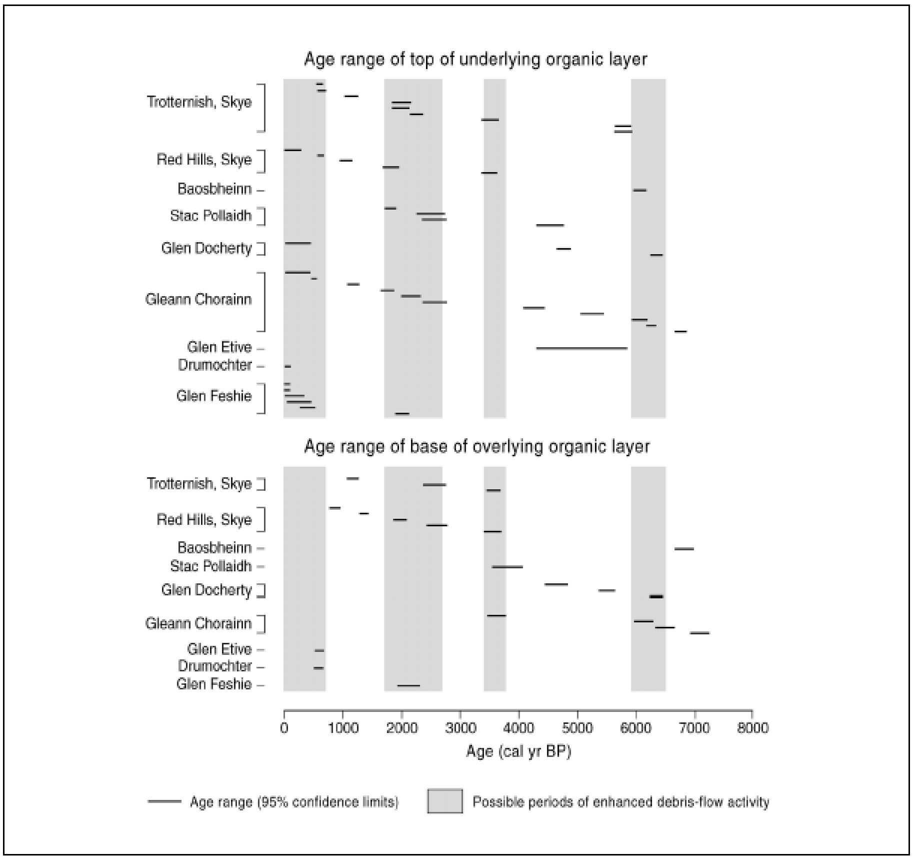


Figure 2.9: Calibrated radiocarbon age ranges associated with debris flow occurrence at 9 sites in the Scottish highlands over the past 7000 years showing possible episodes of increased flow activity. The length of each horizontal bar indicates the 95% confidence limits for each calibrated age (Ballantyne, 2004a).

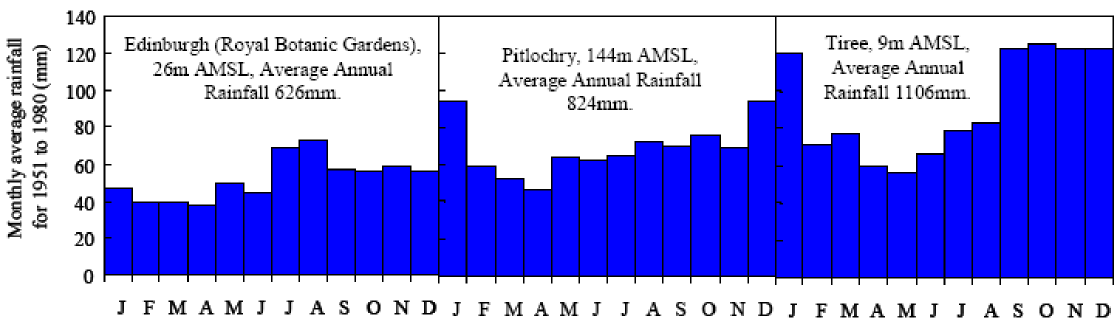


Figure 2.10: Average rainfall patterns at selected location in eastern (Edinburgh), central (Pitlochry) and western (Tiree) Scotland (Winter *et al*. 2007).

2.6 Hazardous Debris Flows

The majority of debris flows in Scotland occur in remote areas (Innes, 1983a) and are therefore low hazard events which have at most minor economic impacts associated with damage to fencing, forestry and estate roads or through the reduction of livestock grazing potential (Ballantyne, 2004a). However, occasionally debris flow activity does impact on important slope foot infrastructure most commonly affecting transport communications in the shape of the trunk road, local road and railway networks (Ballantyne 2004a; Winter *et al*. 2005). Debris flows in Scotland tend to be smaller in size than those in areas of higher relief (Innes, 1985) and accordingly the debris flow geohazard is less severe. For example, whereas there is no record of loss of life or serious injury as a consequence of debris flow activity in Scotland, debris flows in British Columbia, Italy, Japan, South East Asia, Nepal and South America have led to the loss of numerous lives (Takahashi *et al*. 1981; Hungr *et al*. 1984; Must, 1999; Wieczorek *et al*. 2001; Lopez *et al*. 2003; Fernandes *et al*. 2004; Chen & Petley, 2005; Petley *et al*. 2007). Nevertheless, the volumes of material and the size of particles involved in some Scottish debris flow events demonstrate the potential for serious injury or death (figure 2.11) (Winter *et al*. 2005). The potential severity of the Scottish debris flow geohazard has also been highlighted by instances where vehicles and buildings have been impacted by debris such as at the A887 at Invermoriston in 1997 (Nettleton *et al*. 2005), the A9 near Dunkeld and the A83 west of Cairndow in 2004 (Winter *et al*. 2006) on the A83 near Rest and be Thankful in 2007 (The Scotsman, 2007) and on the A85 at Glen Ogle in 2004 where 20 vehicles were trapped by debris flows necessitating the helicopter airlift rescue of 57 people (figure

2.12). An unoccupied roads operator vehicle was also swept downslope during this event.

Debris flow events affecting slope foot infrastructure can also cause considerable socio-economic impacts due to loss of utility and infrastructural damage (Winter *et al*. 2005). For example, debris flows generated by a rainstorm in Lochaber and Appin in May 1953 blocked bridges and culverts and caused £130,000 of damage in Argyllshire (Common, 1954; Ballantyne, 2004a). More recently, during the particularly wet August of 2004, three debris flow events impacted upon the Scottish road network. These occurred at the A83 to the west of Cairndow on the 9th of August, the A9 to the north of Dunkeld on the 11th of August and at the A83 in Glen Ogle on the 18th of August (Winter *et al*. 2006). The A85 which carries up to 5,600 vehicles per day during peak seasonal times (typically in either July or August) was closed for four days whereas the A83, which carries up to 5,000 vehicles per day, and the A9, which carries 13,500 vehicles per day, were both closed for two days resulting in serious traffic disruption (Winter *et al*. 2005, 2006, 2007). Debris flows also led to trunk road closures at Letterfindlay in January 2005 and on the A83 at Rest and be Thankful in November 2007 where the road was un-operational for several days while remedial work was carried out (The BBC, 2007).

Figure 2.11: Large boulders (estimated weight up to 9 tonnes) in debris flow deposits on the A83 near Cairndow, 11th of August 2004 (Winter *et al*. 2006).

Figure 2.12: Hazardous Scottish debris flows: 1. A9 north of Dunkeld, 9th of August 2004. 2. A85 at Glen Ogle, 18th of August 2004 (Winter *et al*. 2006).

2.7 Future Trends: Climatically enhanced debris flow geohazard

It has been suggested that a wettening of Scotland's climate over the past few decades has increased the likelihood of debris flow generation (Smith, 1995; Winter, et al. 2005; Met Office, 2008). Therefore, future climatic changes encompassing a general increase in wetness (and thus an increased probability of high antecedent moisture conditions) and storm frequency are likely to result in an upturn in the number of debris flow events. Climatic changes such as increases in annual rainfall totals and storminess are a symptom of the warming of the Earth's atmosphere which has seen a rise in temperatures of approximately 0.74^{o}C on average across the globe between 1906 and 2005 (UKCIP, 2008) (figure 2.13). It can be argued that much of this observed warming can be closely correlated with human induced increases in atmospheric concentrations of greenhouse gases *inter alia* Carbon Dioxide (CO_2), Nitrogen Oxides (NO_x) and Methane (CH_4) since the commencement of the industrial revolution in 1750AD (Houghton *et al*. 1996). However, it is important to acknowledge that any rises in global temperature and resultant climate change due to anthropogenic influences will be superimposed on background values of natural climatic variation (IPCC, 2001).

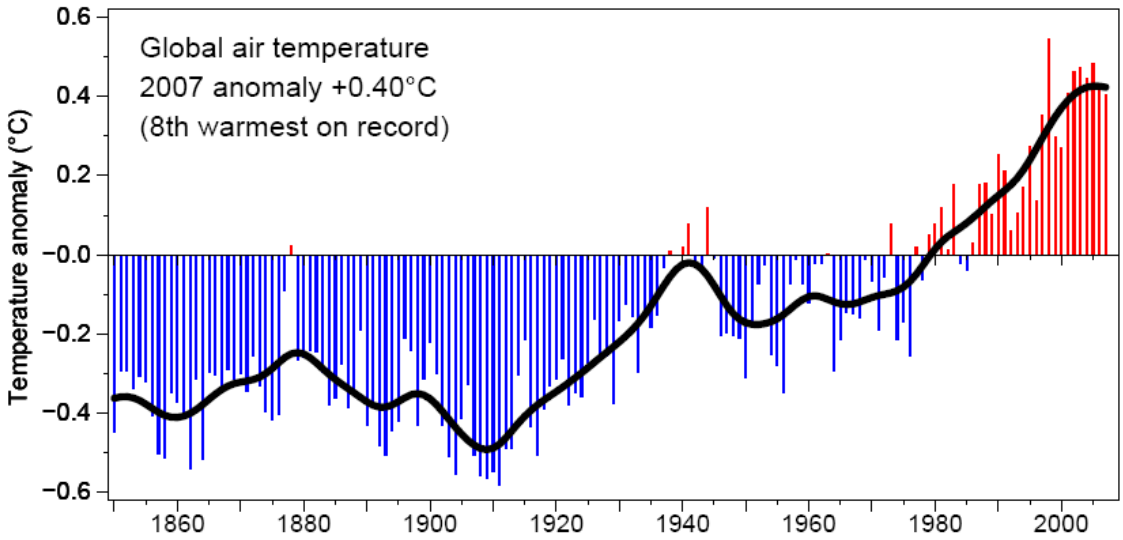


Figure 2.13: Time series showing the combined global land and marine surface temperature record from 1850 to 2007 indicating an increase in global air temperature over the course of the instrumental record (Climatic Research Unit, 2008).

2.7.1 Projected climatic change for Scotland

If the current observed increase in global temperatures can be said to be as a result of anthropogenic discharges of greenhouse gases, then it is possible to make projections of future climate change using sophisticated mathematical models of global climate systems known as General Circulation Models (GCMs) and higher resolution regional circulation models (RCMs) (Conway, 1998). Climate change projections for Scotland up to the 2080s have been made by the Hadley Centre’s HadRM3 regional circulation model under varying UK Climate Impacts Programme 2002 (UKCIP02) greenhouse gas emission scenarios (low, medium-low, medium-high and high emission scenarios).

Under the UKCIP02 scenarios, it is projected that the average annual temperature in Scotland will be between 1°C and 4°C warmer depending on the region and scenario by the 2080s (UKCIP, 2008) (figure 2.14). This rise in temperatures can be expected to result in a higher energy atmosphere and a more vigorous hydrological cycle with consequential increases in the frequency and the intensity of rainstorms (Conway, 1998) Accordingly, the models forecast that high magnitude precipitation depths will rise by between 10% and 30% by the 2080s (Winter *et al*. 2005).

Predicted annual and seasonal changes in precipitation for Scotland vary greatly according to location and emission scenario. Annual changes are anticipated from 0 to -10% for all scenarios across Scotland (Werritty & Chatterton, 2004). The most extreme seasonal changes for low emissions are in the winter where, by the 2080s, increases in excess of 15% are predicted for some parts of eastern Scotland whilst under high emission scenarios winter precipitation increases in excess of 30% are anticipated for some eastern areas. In the western Highlands precipitation increases are less pronounced remaining lower than 15% for even medium-high to high emission scenarios (UKCIP, 2008). However, it is important to note that in absolute terms the west is expected to remain markedly wetter than the east due to the continued endurance of a distinct west-east precipitation gradient (Werritty & Chatterton, 2004) (figure 2.15). Summer precipitation decreases of 0-15% in the north and 15-30% in the south of Scotland are predicted by the 2080s under the low emissions scenario. These become reductions of 15-30% in the north and more than 30-45% in the south under the high emissions scenario (UKCIP, 2008) (figure 2.16). Despite the increases in winter precipitation, it is expected more precipitation will fall as rain rather than snow as a consequence of increased temperatures (Werritty & Chatterton, 2004).

As a result of the predicted changes in climate, average soil moisture content is expected to increase by between 3% to 5% in the winter and decrease by 10% to 30% during the summer by the 2080s (Galbraith *et al*. 2005). Changes in soil moisture levels in the autumn are predicted to be similar to those for the summer due to an anticipated inertia in soil moisture recovery following hotter and drier summers. The reduction in soil moisture content is also forecasted to be most prominent in southern and eastern parts of Scotland (Galbraith *et al*. 2005).

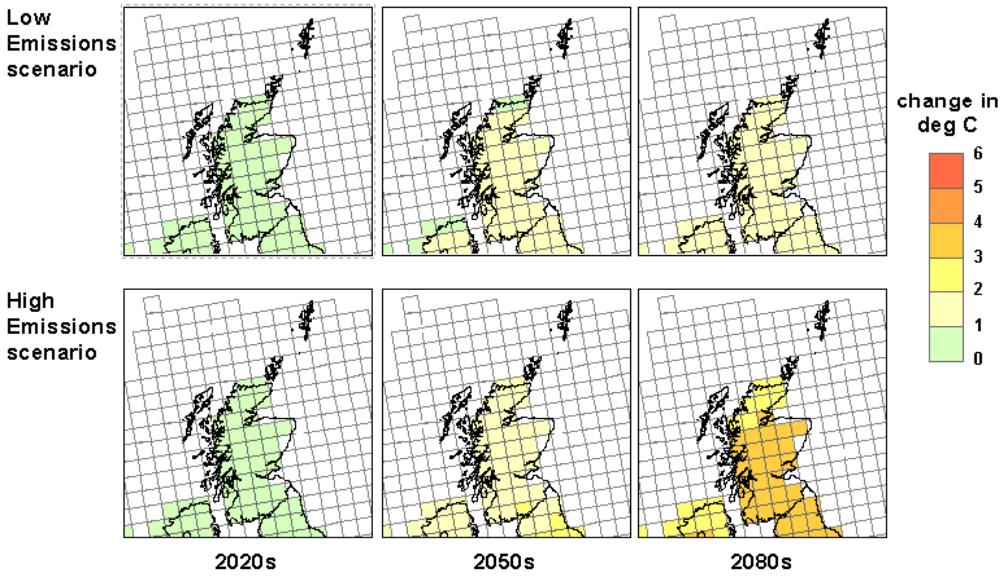


Figure 2.14: Projected change in Scottish annual average daily temperature. Source: UKCIP02 Climate Change Scenarios (funded by Defra, produced by Tyndall and Hadley Centres for UKCIP) (UKCIP, 2008).

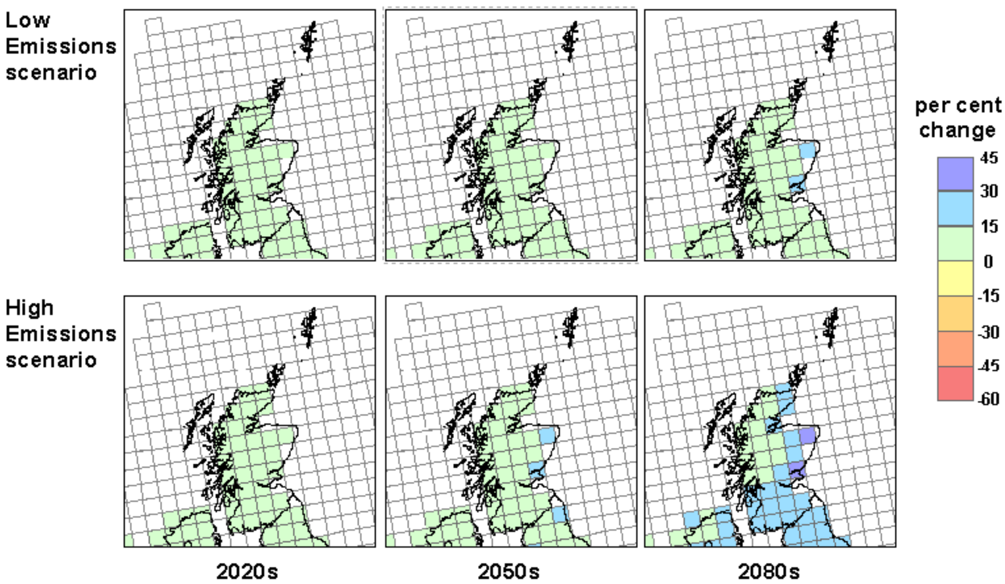


Figure 2.15: Anticipated percentage change in winter precipitation for Scotland. Source: UKCIP02 Climate Change Scenarios (funded by Defra, produced by Tyndall and Hadley Centres for UKCIP) (UKCIP, 2008).

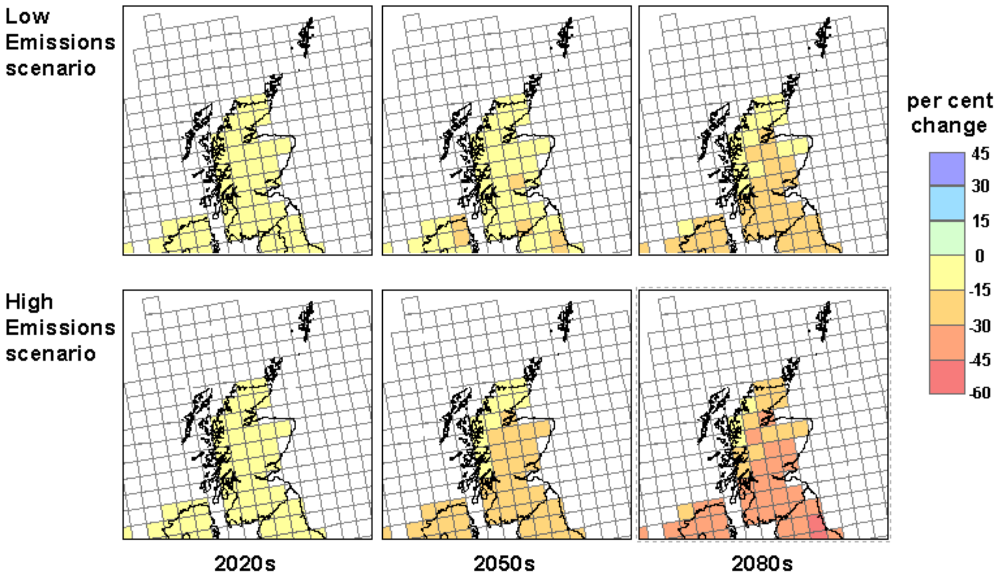


Figure 2.16: Anticipated percentage change in summer precipitation for Scotland. Source: UKCIP02 Climate Change Scenarios (funded by Defra, produced by Tyndall and Hadley Centres for UKCIP) (UKCIP, 2008).

2.7.2 Implications of climate change for the debris flow process

Anticipated increases in intense rainfall can be expected to result in an upturn in the occurrence of debris flow activity across Scotland. This will lead to a more potent debris flow geohazard presenting a greater risk to transport communications and buildings in areas of high relief due to a climatologically forced increased frequency of debris flow events (Milne & Davies, 2007). The anticipated increases in rainfall in the east may be expected to result in a more substantial increase in debris flow activity on hillslopes in eastern Scotland compared to western Scotland where smaller projected increases in rainfall will perhaps result in a more subtle upturn in debris flow activity. In the summer, hotter temperatures and decreases in precipitation are expected to lead to reductions in summer soil moisture. Therefore, as high antecedent soil moisture conditions are a prerequisite to optimal flow generation, a summer reduction in the frequency of debris flow activity may occur under projected climatic conditions. However, although a downturn in overall summer precipitation totals is anticipated by the 2080s, summer rainstorm intensity is predicted to increase concurrently by up to 10% (Winter *et al*. 2005). Consequently, it is possible that an upturn in debris flow generation during summer months may occur due to dissipation of soil suctions at shallow depths by the downward migration of a wetting front into unsaturated soil during intense rainstorms (Fourie, 1996; Springman *et al*. 2003; Wheeler *et al*. 2003; Winter *et al*. 2007).

Increased desiccation of soil during drier summer months will potentially provide abundant pathways for water infiltration into slope material when a period of heavy rainfall follows dry weather. Therefore, under projected climatic conditions a high frequency of debris flows may be expected to occur as wetter weather commences in the autumn. Increases in winter precipitation and soil moisture content can also be expected to lead to a greater frequency of debris flow during winter months although the potential for debris flow generation in Scotland associated with snowmelt can be expected to decrease due to a forecasted reduction in snowfall. Accordingly, under UKCIP02 scenarios, meteorologically driven seasonal episodes of slope instability may occur by the 2080s as a result of enhanced autumn infiltration through cracks in the soil mantle and winter percolation saturation of the soil (Milne & Davies, 2007). However, it is important to acknowledge that inaccuracies in climate change projections made by the climate model will also compromise the accuracy of associated predictions on future debris flow trends (Winter *et al*. 2005).

2.8 Summary and Requirements for Research Project

Debris flows are normally triggered as a consequence of high magnitude rainfall typically initiating as shallow translational slides which make the transition from a sliding to a flow mass movement. Debris flows in Scotland can be subdivided into two simplified types of flow. These are hillslope flows which occur on open, topographically unconfined slopes, and channelised flows which are contained for at least part of their length within a stream channel or bedrock gully. There is a complex suite of contributory factors that contribute to the susceptibility of any given hillslope to debris flow activity. These can be broadly categorised as topographic, material and biogenic/anthropogenic contributors. Topographic factors include the slope gradient and the influence of hillslope morphology on surface and subsurface water flow, material controls largely relate to the strength and permeability of hillslope materials and biogenic/anthropogenic factors generally encompass factors such as root cohesion and the effects of overgrazing from livestock and deforestation.

Observations of lithologically enforced higher debris flow densities have been made on hillslopes underlain by granitic and sandstone bedrocks compared to those characterised by finer grained metamorphic and extrusive igneous lithologies. This trend has been attributed to higher permeability in the sandier matrixes developed over coarse grained bedrocks facilitating rapid increases in pore water pressures during high magnitude rainfall. However, in previous research on Scottish debris flow activity there has been a lack of consideration of the geotechnical controls on the spatial density of debris flow. In particular there has been no investigation of hydraulic transmissivities and strength parameters in source area materials yielded from varying lithologies. The influence of slope topography on the generic susceptibility of hillslopes to debris flow has also not been considered in detail during previous research into Scottish debris flow phenomena. It may conceivably be the case that higher observed debris flow densities at sites with coarser grained bedrocks may be a function of the persistence of steep slopes or a higher frequency of rock outcrops and slope concavities rather than as a consequence of the material properties. In this research project, attempts will be made to address these omissions. The effect of varying rainfall totals on debris flow spatial densities at different sites has also been overlooked in previous research. In order to take into consideration the effect of varying prevalent meteorologic conditions on propensity to debris flow measured debris flow densities should be normalised with the average annual rainfall totals at the investigated site.

The majority of Scottish debris flows occur in remote areas and are therefore low hazard events. However, when slope foot infrastructure (commonly roads and railways) are exposed to debris flow the process represents a significant geohazard. Debris flow events can also cause considerable socio-economic impacts due to loss of utility and infrastructural damage. Debris flows have occurred in Scotland throughout the Holocene although lichenometric and geomorphic evidence indicate an upturn in the temporal frequency of debris flow activity over the past few centuries. Observed data, including an apparent upturn in the number of debris flows impacting on the Scottish road network, also points to an increased frequency debris flow activity in recent years. It has been suggested that such an increase in flow activity can be attributed to a contemporaneous increased occurrence of high magnitude rainstorms. As a consequence of projected climatic change that will see an upturn in the severity and frequency of extreme rainfall events coupled with a wetter winter climate, it is anticipated that there will be a climatologically forced increase in the potency of the

Scottish debris flow geohazard over the coming decades. This underlines the necessity to understand as much as possible about the debris flow process to allow optimal management of a geohazard of increasing severity.

3. Study Sites

Six study sites with differing lithologies were chosen across Scotland for investigation of the topographic and material controls on debris flow activity (figure 3.1). The study sites were selected where debris flow activity has been recorded in the past and are situated across upland Scotland in order to avoid bias towards areas with higher average annual precipitation such as the western highlands. The location and physical characteristics of each site are outlined in this chapter.

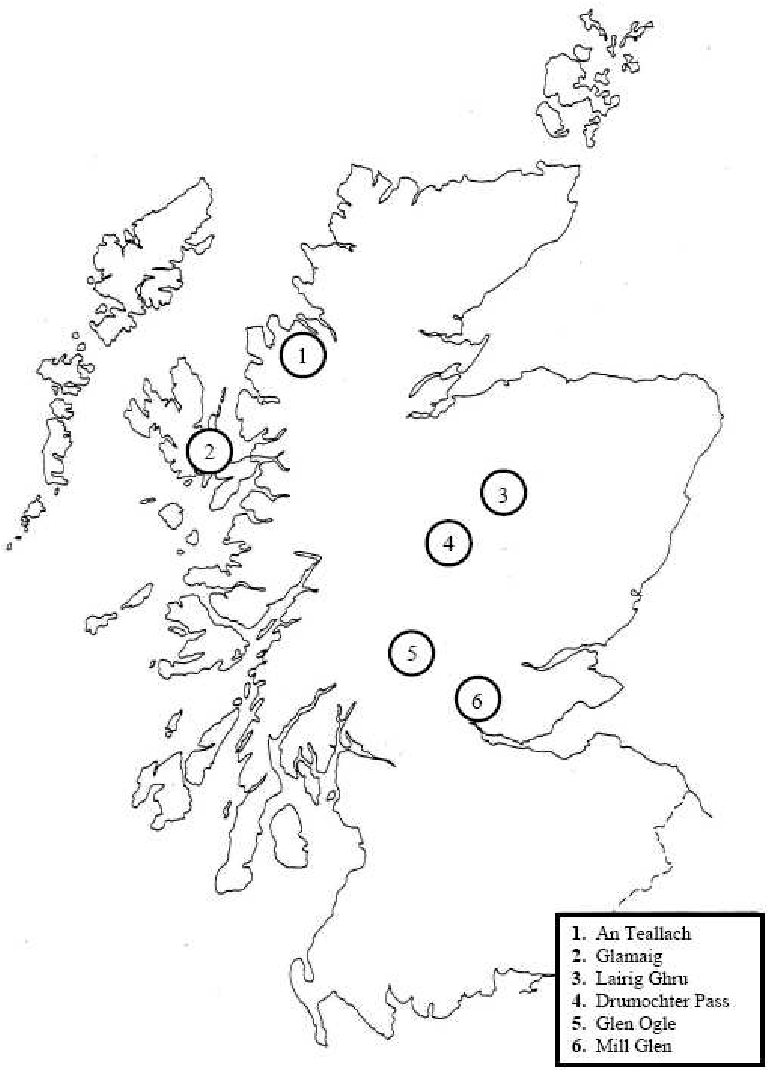


Figure 3.1: Location of study sites.

3.1 An Teallach

The An Teallach study site is centred on the northerly slopes of Glas Mheall Mor, the most northern peak in the An Teallach mountain massif in the North West Highlands (57º49'N, 5º15'W) (figure 3.2). The vegetation at the site is characterised by sparse grassland and heather cover and the land is utilised for sheep grazing. The site is underlain entirely by Torridonian Sandstone (Peach *et al*. 1913). It has been suggested that the upper slopes of An Teallach remained exposed above the last Scottish ice sheet as a nunattak at the last glacial maximum *c.*18.5 ka BP (Ballantyne, 1993) whilst during the Loch Lomond Stadial a small glacier existed at the site in the confines of Coire a Mhuillin (Sissons, 1977). The extent of this glacier is clearly delimited by a prominent terminal moraine (Ballantyne & Eckford, 1984). The mean annual rainfall for the study site is 2489 mm (Institute of Hydrology, 1999).

The study site and the surrounding area is noted for what has been described as "probably the finest assemblage of high-level aeolian and niveo-aeolian features in Great Britain" (Ballantyne, 1993) formed by the deflation of surrounding plateau surfaces by wind erosion followed by the deposition of the sandy regolith on nearby slopes (Godard, 1965; Ballantyne & Whittington, 1987; Ballantyne, 1993; Ballantyne & Morrocco, 2006). The upper slopes of Glas Mheall Mor are mantled by frost shattered detritus comprised of predominantly sub-angular, elongate clasts embedded in a coarse, sandy matrix (Ballantyne, 1993; Ballantyne & Harris, 1994). Towards the eastern part of the study site a relict talus slope characterised by an average altitude of 640m and an average relief of 61m has accumulated beneath a 20-50m high rockslope (Ballantyne & Eckford, 1984). Debris flow activity has been recorded on the north facing slopes of Glas Mheall Mor in previous research (Ballantyne & Eckford, 1984;

Ballantyne, 1993). Lichenometric data suggests intermittent debris flow activity at the site since *c*. 1750 AD (debris flow deposits older than this age having been buried by more recent flows) with likely periods of increased activity between 1890 and 1920 and during the 1970s (Innes 1983a, Ballantyne, 2004a).

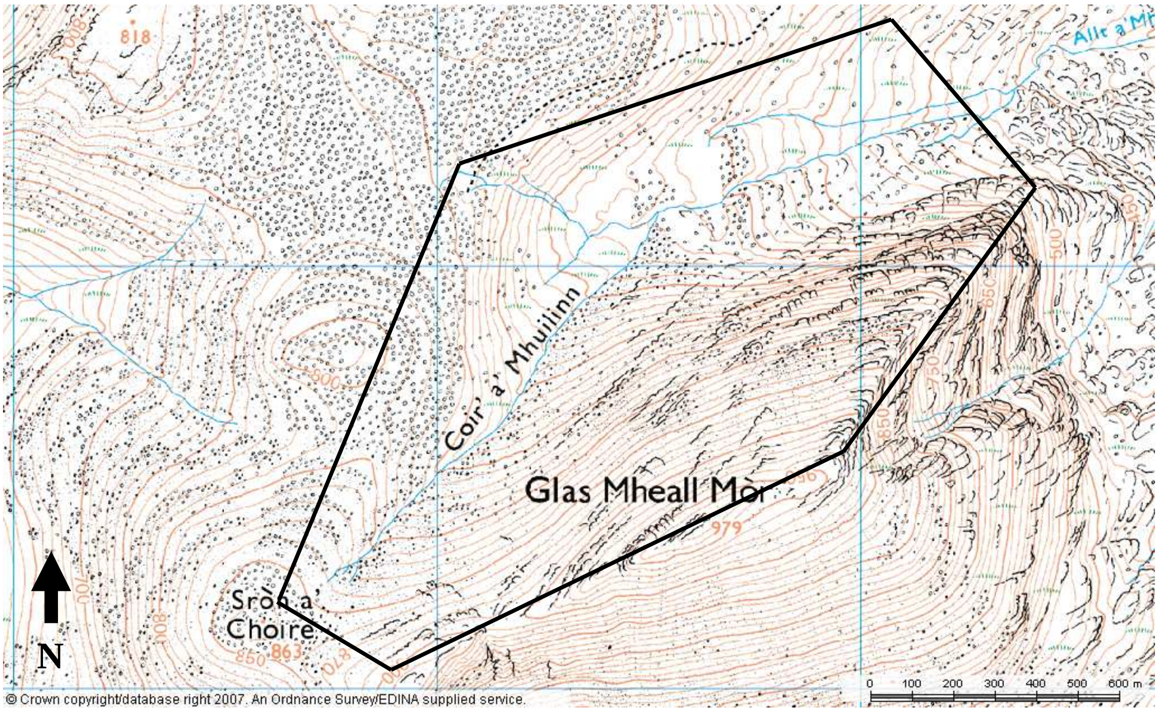


Figure 3.2: Map of the An Teallach study site.

3.2 Glamaig

Glamaig is a steep sided mountain in the Western Red Hills on the Isle of Skye (57º17'N, 6º6'W) with a maximum altitude of 775 m AOD. The study site is situated on the southern and eastern facing slopes of the mountain (figure 3.3). The lithology of the mountain comprises of granite bedrock overlain by a basalt roof pendant (Bell & Williamson, 2002). The basalt bedrock is situated above the debris flow source areas at the eastern side of the study site, but towards the west the basalt lithology underlies the debris flow source areas. Consequently, debris flow activity in regoliths developed over both fine grained basalt and coarse grained granite can be investigated in close proximity. The study site was last glaciated during the Loch Lomond Stadial when a glacier flowed around the lower slopes of the mountain leaving the upper slopes exposed and subject to intense periglacial activity (Ballantyne, 1989) (figure 3.4). Vegetation at the site comprises of grassland and moorland species. The land is utilised for livestock grazing. Exact data for the mean annual rainfall at the site was not available from the Flood Estimation Handbook (Institute of Hydrology, 1999). However at Sgurr Na Coinnich, a 739 m peak in southern Skye 25 km ESE from Glamaig (NG 763 822), the mean annual rainfall is 2888 mm (Institute of Hydrology, 1999). Due to the relatively close proximity and similar altitude of Sgurr Na Coinnich, this figure can be considered as broadly indicative of the value at Glamaig.

The steep slopes of Glamaig are mantled by relict talus slopes which were largely developed during the colder climate of the Late Glacial. These slopes have subsequently been reworked by mass movement processes during the Holocene. Curry (2000a) observed a high spatial density of debris flow at the study site and carried out radiocarbon dating at a section cut in debris flow deposits. The radiocarbon results suggest periods of instability occurring immediately before 3300 ± 50 yr BP, 1985 ± 55 yr BP, 1410 ± 40 yr BP, 940 ± 45 yr BP and subsequent to 710 ± 45 yr BP. These radiocarbon dates and the stratigraphy of the sampled section suggest that reworking of slope material over the past 710 years has been frequent enough to prevent the development of an organic soil on top of the debris deposits (Curry, 2000a).

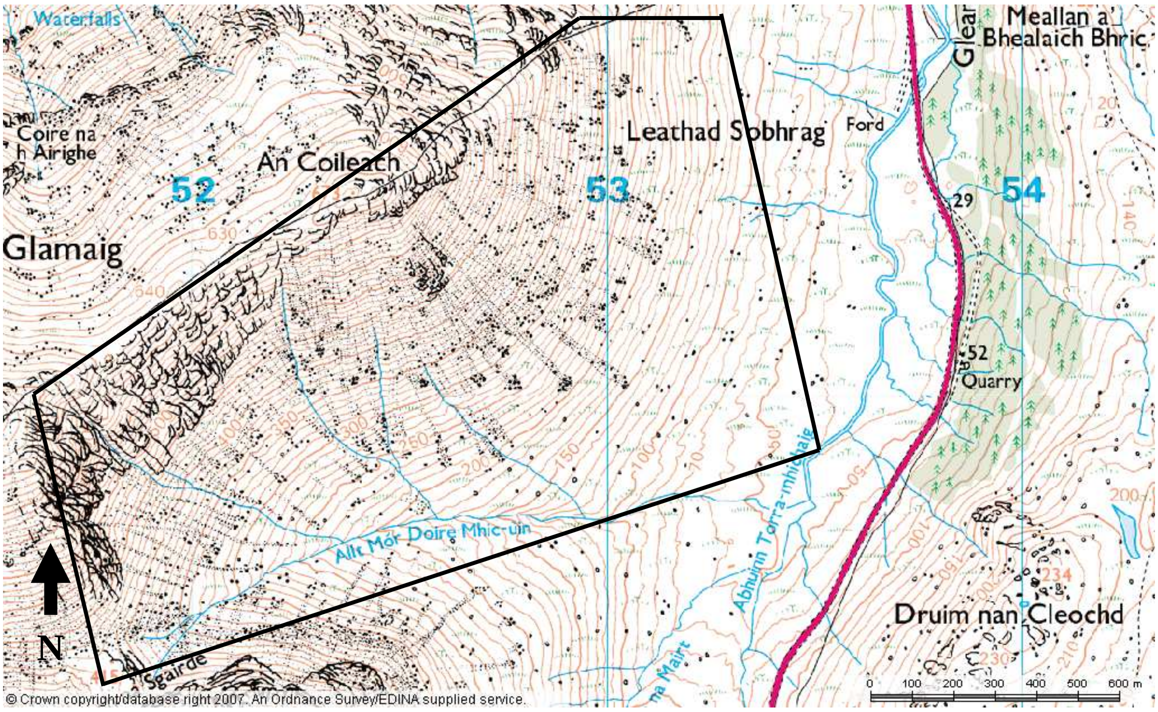
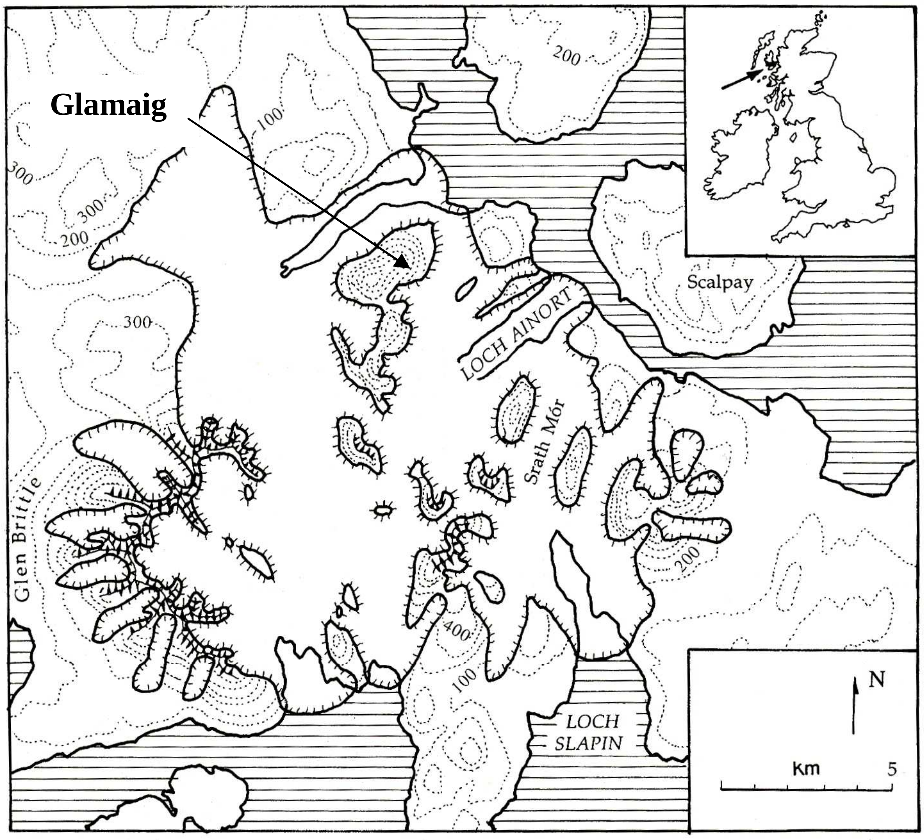


Figure 3.3: Map of the Glamaig study site.



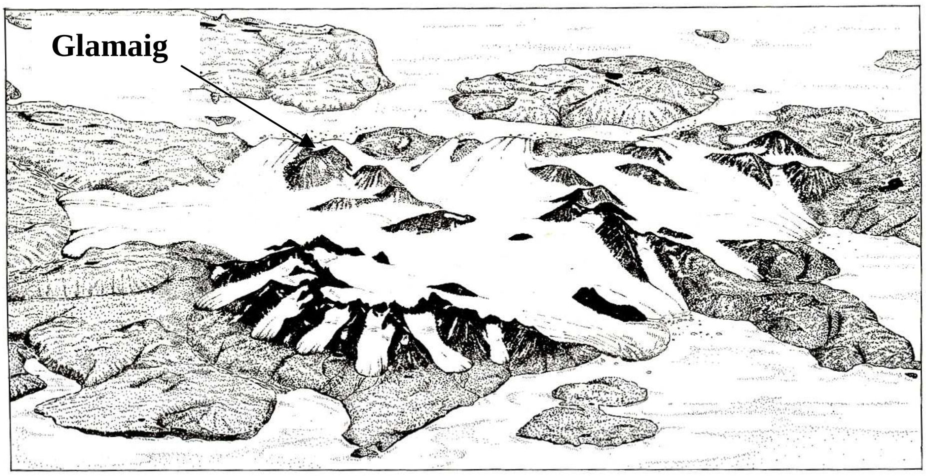


Figure 3.4: Reconstruction of the Loch Lomond Stadial icefield on the Isle of Skye showing the extent of glacial ice around the Glamaig study site (Ballantyne, 1989).

3.3 Lairig Ghru

The Lairig Ghru is a steep sided glacial breach valley which cuts through the Cairngorm Mountains between the summits of Ben MacDui (1309 mAOD) and Braeriach (1296 mAOD) (Luckman, 1992). The study site comprises a 1 kilometre stretch of the west facing slope of the pass (57º06'N, W3º42') (figure 3.5). At the study site the Lairig is approximately 1 km wide and has a relief of approximately 300 m. The solid geology of the study site is coarse-grained Cairngorm Granite. The slopes of the Lairig are largely covered by exposed frost shattered detritus which has been reworked by debris flow activity and avalanching (Luckman, 1992). The study site was probably deglaciated by *c*. 13 ka BP and was not subsequently reoccupied by ice during the Loch Lomond Stadial (Sissons, 1974, 1979b). The mean annual rainfall total is 2038 mm (Institute of Hydrology, 1999).

Previous investigation into debris flow activity at the Lairig Ghru has identified a high spatial and temporal flow frequency the site (Ballantyne, 2004a). Observations from historic aerial photography (Innes, 1982) and field observations (Luckman, 1992) have indicated that at least three major debris flow events have occurred at the study site since the 1930s suggesting a recurrence interval of approximately 20 to 30 years (Ballantyne, 2004a). Innes (1982) observed fresh looking landforms indicative of recent debris flow activity on air photos dating from 1946 whilst a further set of recently formed flows was apparent on aerial photography from 1961 (Ballantyne, 2004a). It has been suggested that the latter assemblage of debris flows was triggered during a deep depression from the 12th to the 14th August 1956 in which an estimated 150 mm fell over the Cairngorm Mountains with a maximum intensity of 86 mm in 24 hours (Baird & Lewis, 1957; Ballantyne 2004a).

Yet another array of recent debris flows which had obliterated much of the earlier assemblage was observed during field visits in 1980 (Luckman, 1992). Ballantyne (2004a), whilst highlighting the occurrence of earlier potential landslide generating storms in 1976 and June 1978, has suggested that these flows were most likely triggered by a rainstorm with a 24 hour rainfall total of approximately 80mm in August 1978. It has been calculated that at least 71 debris flows were generated in the Lairig Ghru during the 1978 storm (Innes, 1983a; Ballantyne, 2002a). However, no significant debris flow activity has occurred at the site since this event (Ballantyne, 2002a; 2004a)

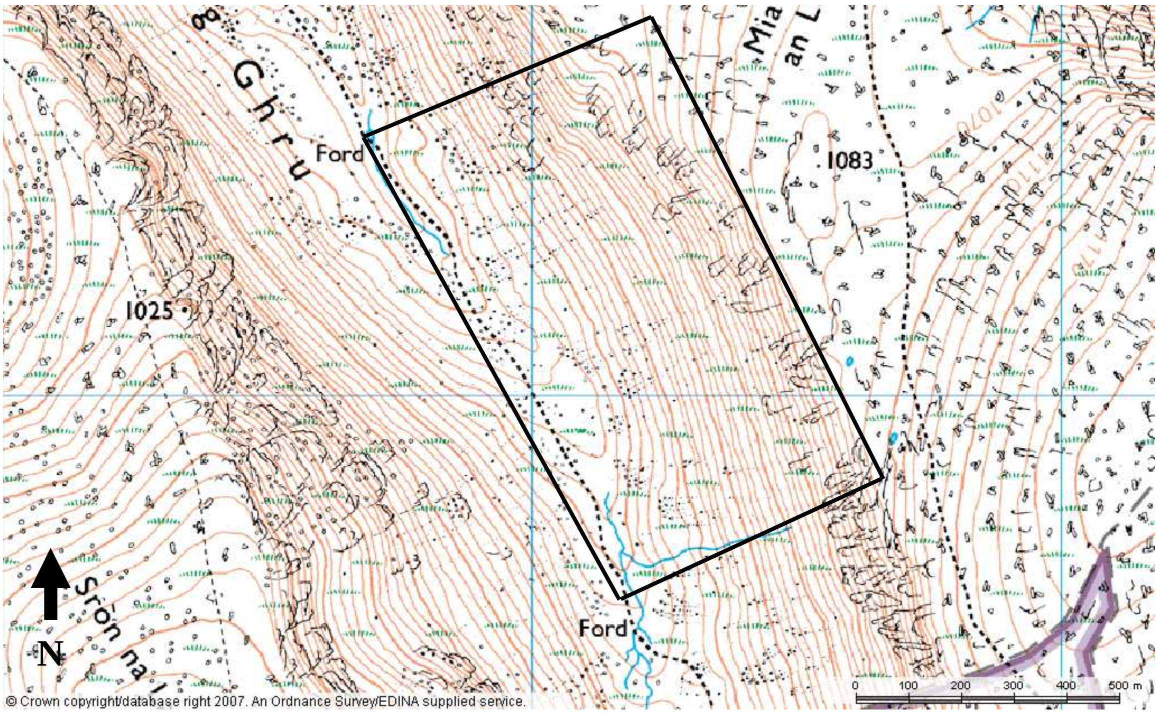


Figure 3.5: Map of the Lairig Ghru study site.

3.4 Pass of Drumochter

The Pass of Drumochter is located in the central Grampian Mountains (56º51'N, 4º15'W). The pass is approximately 500 m wide with a relief of up to 290 m (figure 3.6). The study site is an important transport route as highlighted by the presence of the A9 trunk road and a railway line. The site was also chosen as a route for a military road built in the early 18th century. The slopes of the pass are mantled by thick deposits of glacial till which becomes thinner higher up the pass giving way to gelifluctate on the upper slopes and mountaintops. The floor of the pass is dominated by an abundance of hummocky or recessional moraines which delimit the staggered decay of glacial ice during the late Devension. The timing of deglaciation in the Pass of Drumochter and thus the age of glaciogenic drift at the study site is a matter of some conjecture with some researchers assigning a Loch Lomond Stadial origin (*c*.11 ka – 10 ka BP) (Sissons *et al*. 1973; Sissons, 1974; Benn & Ballantyne, 2004) whereas others interpret an older genesis from the wastage of the last Scottish ice sheet at the culmination of the Dimlington Stadial (*c*.27 ka-13 ka BP) (Lukas, 2004; Merritt *et al*. 2004; Mitchell & Merritt, 2004). The underlying bedrock at the site consists of monotonous sequences of psammitic schist and localised semipelite derived from shallow marine deposits which were metamorphosed during the Grampian Orogeny (Stephenson & Gould, 1995). These rocks generally weather rapidly when exposed to the contemporary Scottish climate, resulting in extensive periglacial activity (Lukas, 2002). The vegetation at the site is characterised by grassland and bracken cover. The mean annual rainfall (1961 -1990) at the site is 1797 mm (Institute of Hydrology, 1999).

Previous research on debris flow activity at the Pass of Drumochter has focused on four large debris cones on the eastern slopes of An Torc (Boar of Badenoch) (Ballantyne & Benn, 1994; Curry, 2000a; Ballantyne, 2004b). The debris cones have accumulated from four main drift-cut feeder gullies eroded into the steep (35 to 40°) hillslope (Curry, 1998; Ballantyne, 2004b). These gullies range from 106 to 191 m in length, 12 to 32 m in width and have maximum depths of between 5.5 and 8.3 m (Ballantyne, 2004b). Based on the dimensions of the gullies, a minimal volume of approximately 30,000 m^3 has been proposed for the debris cones (Curry, 1998; Ballantyne, 2004b). The debris cones are largely vegetated indicating extensive stability. However, they do exhibit unvegetated levees and debris lobes known to have been deposited between 1995 and 2000 (Ballantyne, 2004b). Debris flows were also triggered on the west facing side of the pass as a consequence of heavy rainfall in 1978 (A. Werritty pers. comm. 2005). It has been suggested that the available data for the Pass of Drumochter points to a current debris flow return period of 10 – 15 years at the site (Ballantyne, 2004a).

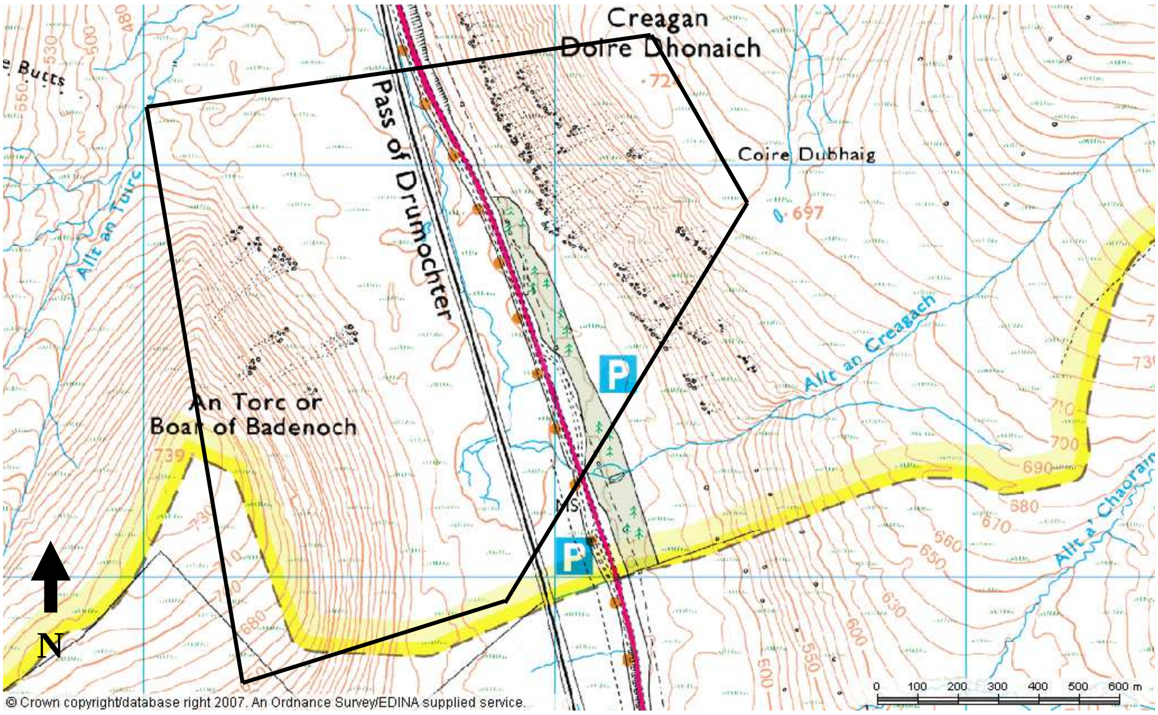


Figure 3.6: Map of the Drumochter Pass study site.

3.5 Glen Ogle

Glen Ogle is located in the southern Grampian Mountains in Stirlingshire, Scotland (56º24'N, 4º18'W) (figure 3.7). The A85 trunk road, an abandoned railway line and a military road dating from the mid 18th century are situated in the glen highlighting the site's historical importance as a transport route. The walls of the glen are relatively steep, existing as rock slopes in many places and rising to maximum altitudes of 719 m AOD at Meall Buidhe on the east side of the Glen and 707 m AOD at Meall Sgallachd on the west side of the glen. The lithology at Glen Ogle is dominated by impermeable upper Dalradian metamorphic rocks, in particular Quartzose-Mica-Schists formed from marine shales during the Caledonian Orogeny (*c*.410 Ma BP) (Craig, 1991). The drift geology of the glen consists of glacial tills deposited during the Dimlington Stadial (*c*.27 ka -13 ka BP) which were then heavily reworked by periglacial activity during the cold climate of the Loch Lomond Stadial (*c*.11 ka-10 ka BP). Thompson (1972) inferred the presence of a Loch Lomond Stadial glacier flowing through the glen and terminating near the village of Lochearnhead at the south-eastern end of the glen. However, N. Golledge (Pers. comm 2007) observed a prominent moraine ridge by Lochan Lairig Cheile *c*. 2 km to the north-east of the study site which may represent the limit of Loch Lomond Stadial ice in the Glen. The higher slopes of the eastern side of the glen decrease in gradient to form a plateau morphology which is largely covered in hill peat deposits.

On the 18th of August 2004 numerous debris flows were triggered in the glen by a high magnitude summer rainstorm. Hourly rainfall data from the Killin and Strathyre tipping bucket rain gauges (located *c*.6km N and *c*.10 km SSW of Glen Ogle) indicate that the most intense rainfall occurred over a two hour period around

1600 GMT and that the peak intensity of the storm averaged at approximately 20mm hr^{-1} over 1 hour or 15mm hr^{-1} over 2 hours (Black *et al*. 2005). However, it is important to acknowledge that the intensity of rainfall can vary significantly over short distances and therefore maximum intensity calculated from the rain gauges may under represent the rainfall intensity experienced at Glen Ogle. This is demonstrated by the fact that the daily rainfall total for the 18^{th} of August measured at the Lochearnhead rain gauge at the southern-eastern margin of Glen Ogle (80.9 mm) is substantially higher than the daily totals collected at Strathyre (43.8 mm) and Killin (56.1 mm). Furthermore, during very high intensity rainstorms tipping bucket rain gauges may not be capable of recording all of the bucket tips leading to under measurement of rain intensity. Prior to the onset of the rainstorm it is likely that the soil moisture content was elevated due to high rainfall totals in the days preceding the 18^{th} of August, particularly over the 8^{th} and 9^{th} of the month when a combined rainfall total of 89 mm was measured at Lochearnhead (figure 3.8). Consequently, it can be inferred that the potential for slope instability on the 18^{th} of August was increased due to high antecedent soil moisture conditions. The rainfall total recorded at Lochearnhead on the 18^{th} of August 2004 has a return period of 10 – 15 years. However, as the majority of rainfall fell over a short period of time it is likely that the return period of the rainstorm is much longer, perhaps up to 300 years (Heald & Parsons, 2005). Two of the debris flows generated by the rainstorm were of a sufficient magnitude and position within the glen to traverse the A85 trunk road which runs through the site, trapping 20 vehicles between them and necessitating the helicopter airlift rescue of 57 people (Winter *et al*. 2005, 2006; Milne *et al*. 2007). The investigation of debris flows at the Glen Ogle study site focus on the debris flows generated during this event.

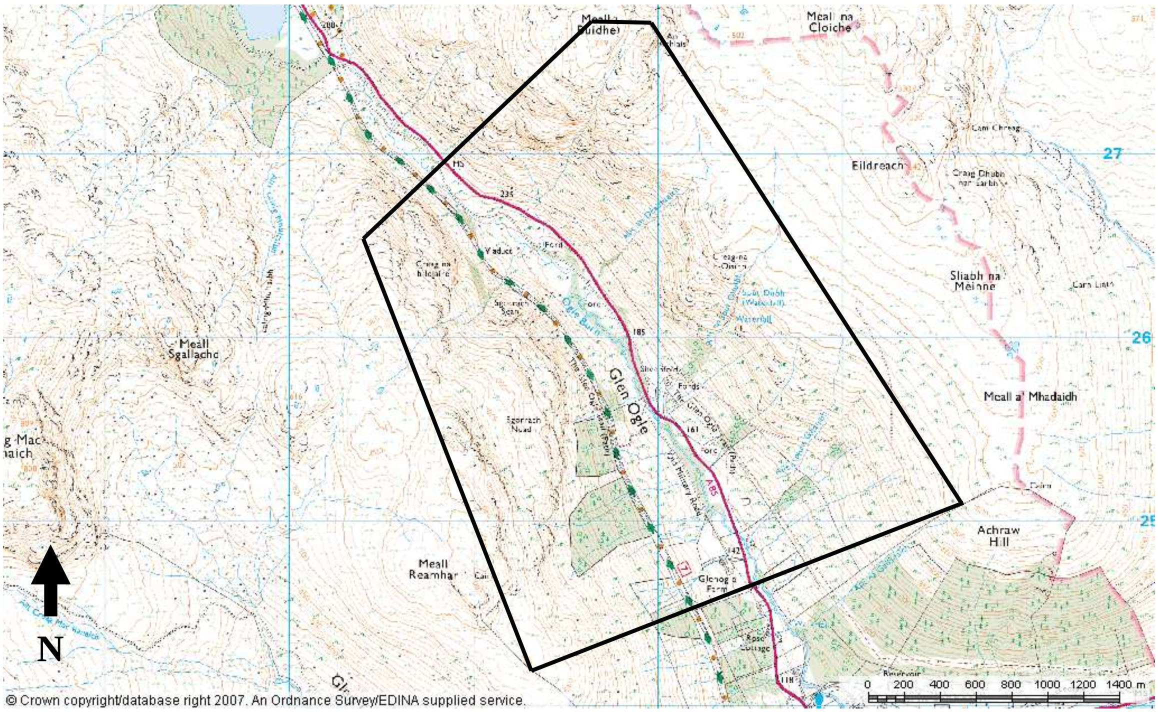


Figure 3.7: Map of the Glen Ogle study site.

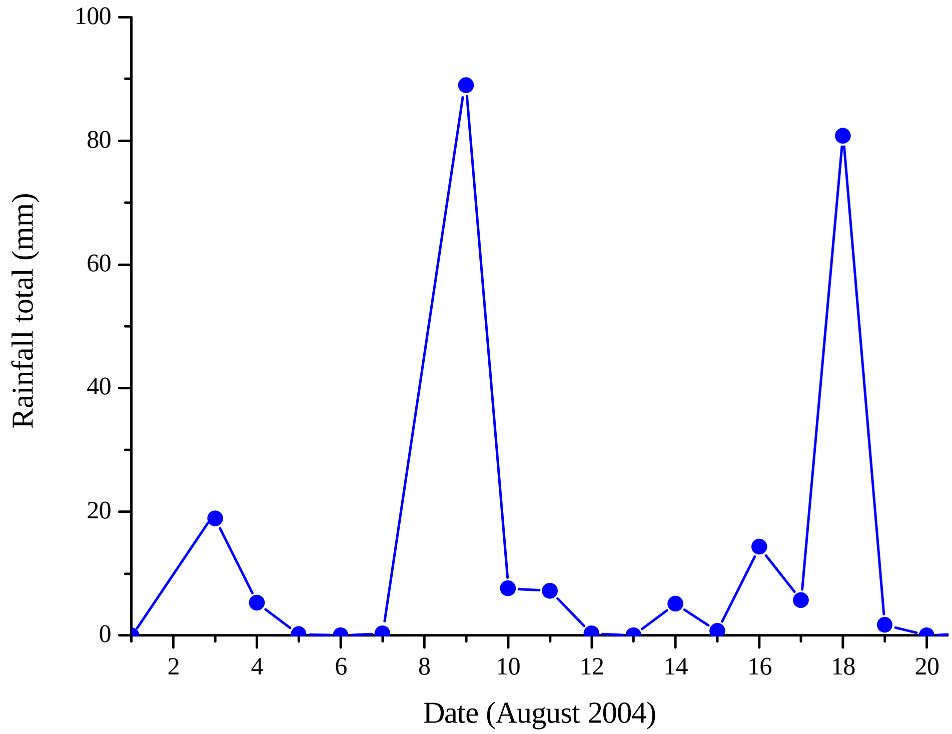


Figure 3.8: Daily rainfall totals measured at the Lochearnhead rain gauge from the 1st of August to the 20th of August 2004. Source: Scottish Environmental Protection Agency.

3.6 Mill Glen

Mill Glen is situated in the Ochil hills in the Midland Valley of Scotland. The study site is located in the upper reaches of the glen on the hillslopes surrounding the Gannel Burn (56º10'23"N, 3º44'30"W) (figure 3.9). The study site is completely underlain by andesitic lavas (Francis *et al*. 1970). The drift geology comprises of till deposited during the Dimlington Stadial glaciation (*c*.27 ka – 13 ka BP) overlain by brown forest soils developed during the Holocene (Jenkins *et al*. 1988). The present day vegetation cover at the study site comprises exclusively of grassland and bracken with the land subject to intensive sheep grazing. The mean annual rainfall for the study site is 1648 mm (Institute of Hydrology, 1999). Debris flow activity was recorded in Mill Glen following long duration, high intensity rainfall on the 4th of November 1984 in the form of a single debris flow which occurred approximately 1 km to the south of the study site (NS 915 985). During the generating storm 68mm of rain fell in 24 hours. Antecedent moisture conditions were likely to be high due to wet weather in the weeks prior to the storm (Jenkins *et al*. 1988).

The debris flow involved 150 m^3 of material and took the form of a channelised debris flow which was initiated in a shallow depression at the head of a gully on a gradient of 23º. The failure plane of this failure coincided with the boundary between the brown forest soil and the underlying glacial till horizon. Piping was observed in soil at the headscar indicating the concentration of subsurface water flow at this location on the hillside (Jenkins *et al*. 1988). No clear geomorphological evidence of this event is apparent in the field today implying total regeneration of the landslide scar since 1984.

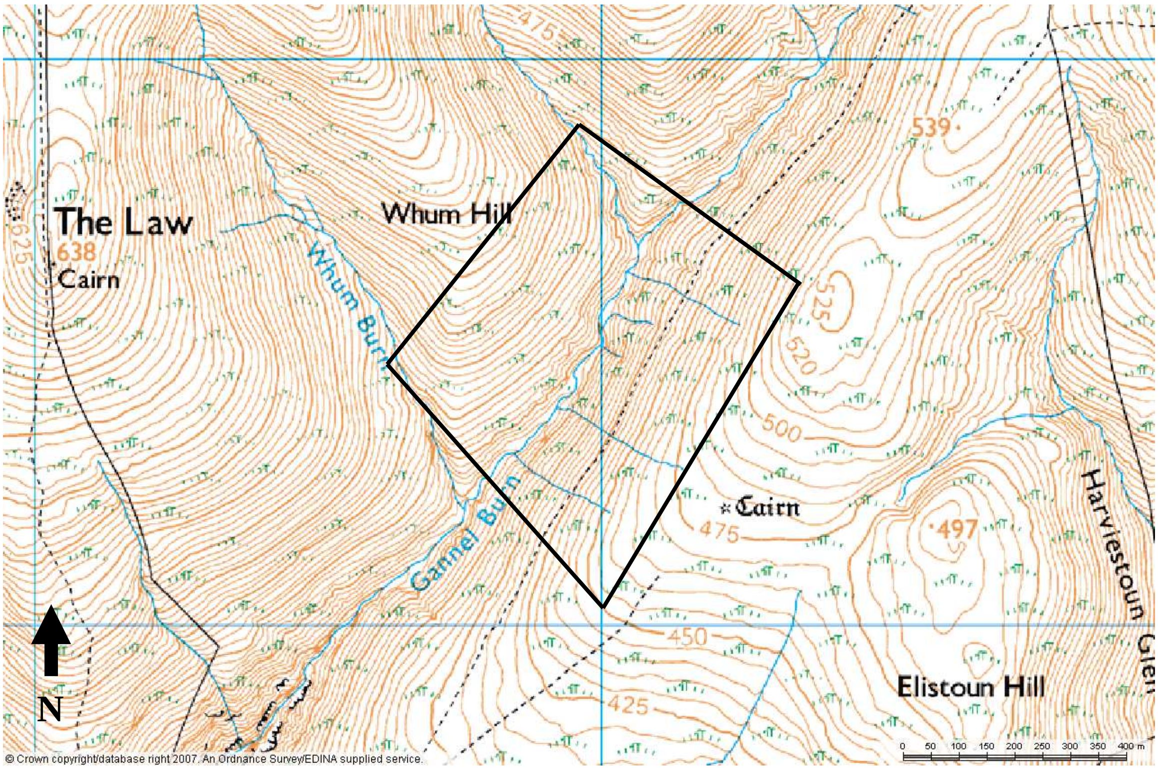


Figure 3.9: Map of the Mill Glen study site.

4. Methodology

The research was carried out using a combination of laboratory and field investigation methods. The material controls on hillslope debris flows were also investigated in greater detail using a simple centrifuge model. The various methods utilised in the research are described in this chapter.

4.1 Field investigation

At each study site an extensive ground survey was carried out in order to investigate the site specific nature of debris flow activity. This involved a visual site assessment, geomorphological mapping and calculation of the spatial frequency of debris flow activity at each study site. Field investigation also encompassed sampling of hillslope materials and measurement of debris flow geometry.

4.1.1 Visual site assessment, mapping and debris flow spatial density

At each study site a comprehensive site assessment was carried out in order to identify the primary landscape characteristics and how they relate to debris flow activity at the study site. Particular attention was paid to important topographic and biogenic factors which can strongly influence susceptibility to debris flow activity such as the presence of persistent steep slopes, stream channels and vegetation cover (see section 2.3.3). Geomorphological maps were produced to accurately record the assemblage of landforms at each site with particular reference to debris flow activity. Where discernable debris flows were observed they were recorded individually on the geomorphological maps. Discernable debris flows are defined as those which can be identified through the enduring presence of a debris flow track and associated debris flow deposits in the form of a fan, a lobe, debris levees or a debris cone. The geomorphological maps were mostly produced from observations made in the field. However, aerial photography was also used to assist in the accurate interpretation and representation of the spatial distribution of debris flows on the maps.

Using the geomorphological maps, the spatial frequency of debris flow activity was determined by dividing the number of observed debris flows at each site by the length of the studied hillslope and expressed as the number of debris flows per kilometre (km^{-1}) (Curry, 1998; MacNaughton, 2004). Each of the study sites have varying rainfall regimes characterised by the strong rainfall gradient in Scotland which results in higher rainfall totals in the western highlands compared to uplands in the east of the country. Due to the importance of antecedent and high magnitude rainfall in generating debris flow mass movement, the potential for flow generation is greater at study areas which experience higher rainfall totals. Consequently, the influence of rainfall was considered by normalising the actual debris flow spatial density at each study site using 1961 -1990 average annual rainfall extrapolated from the Flood Estimation Handbook CD-ROM (Institute of Hydrology, 1999).

4.1.2 Sampling

A total of 9 debris flows were chosen for sampling of soil for investigation of geotechnical properties in the laboratory. To allow investigation on the effect of soil properties on the susceptibility of hillsides to debris flow, it was essential that only source translational landslides identified as having occurred as a result of hydrometeorological induced changes in pore water pressure were sampled. Accordingly, chosen sample sites were all debris flow source translational slides scars on open hillslopes rather than on gully walls where fluvial erosion at the toe of the slope may have triggered failure due to loss of support (Innes, 1983b).

Soil was sampled from exposed profiles at source landslide scars. On selection of a suitable initiating landslide for sampling, the headscar of the landslide was cleared back for approximately 100 mm using a spade. This was done to avoid sampling of material from the surface of the headscar which may have been subject to impoverishment of smaller particles due to exposure to wind and rain. The soil profile was then recorded taking into consideration the thickness of soil horizons and describing the slope material as outlined in BS 5930 (1999). Mineral soil corresponding as closely as possible with the position of the failure plane was sampled from the head scar of the source landslide for investigation of the geotechnical controls on the initiation of the debris flow. The *in situ* density of slope material at debris flow source areas was determined directly in the field. This involved cutting a bench in the exposed soil profile and removing a sample using a trowel. Plastic film was then carefully placed in the void made by the removed sample. A measured quantity of water was poured into the void to establish the volume of the soil sample and the density of the soil was calculated by dividing the mass of the sample by its volume. The soil sample was kept in a sealed container for calculation of water content in the laboratory (Head, 1982). This method for measuring *in situ* density was used in place of the sand replacement method (BSI, 1990) in order to minimise the complexity and weight of equipment in the difficult and remote working environments encountered in this research. However, using this technique, the sand rich soils experienced on Scottish mountain slopes (Innes, 1986) may have been subject to water loss during sampling leading to errors in calculating water content and density. Consequently, the accuracy of the technique was analysed in the laboratory by establishing the maximum water content in samples of silty sand till from Glen Ogle prepared at minimum density and comparing this value with the measured *in situ* water content to establish the potential margin for error. It was found that the maximum water content was within 0.45% of the measured water content, thus verifying the accuracy of the technique. Specimens of peat encountered at source areas were also collected using sample tubes for calculation of unit weight and water content.

4.1.3 Geometric characterisation

The gradient of the hillslope at sampled source landslides was measured using an abney level and the length, breadth and depth of sampled source landslides was measured using a 30 meter measuring tape. The long profiles of debris flow slopes were measured in the field using an abney level to the nearest 0.5º and a 30 m measuring tape. At Glen Ogle, the long profiles of the gullied stream channels which contained debris flows during the transport phase were calculated from the 1:25,000 scale Ordnance Survey map of the area (NN 42/52). This was done at this study site due to the longer and steep nature of these stream channels, which in places are inaccessible due to sheer rock faces. The geometric parameters (e.g. width, length and depth) of deposition fans and lobes of sampled debris flows were also measured to allow for the calculation of the approximate volume of debris deposits thus giving an indication of the magnitude of flow activity. The three axis (a: length, b: width and c: thickness) of larger cobble and boulder sized particles in debris flow deposits were measured using a 30 m measuring tape to determine the size of the largest debris involved the sampled debris flows. The shape of the particles was also recorded in terms of the angularity of the clasts (figure 4.1) (BSI, 1999).

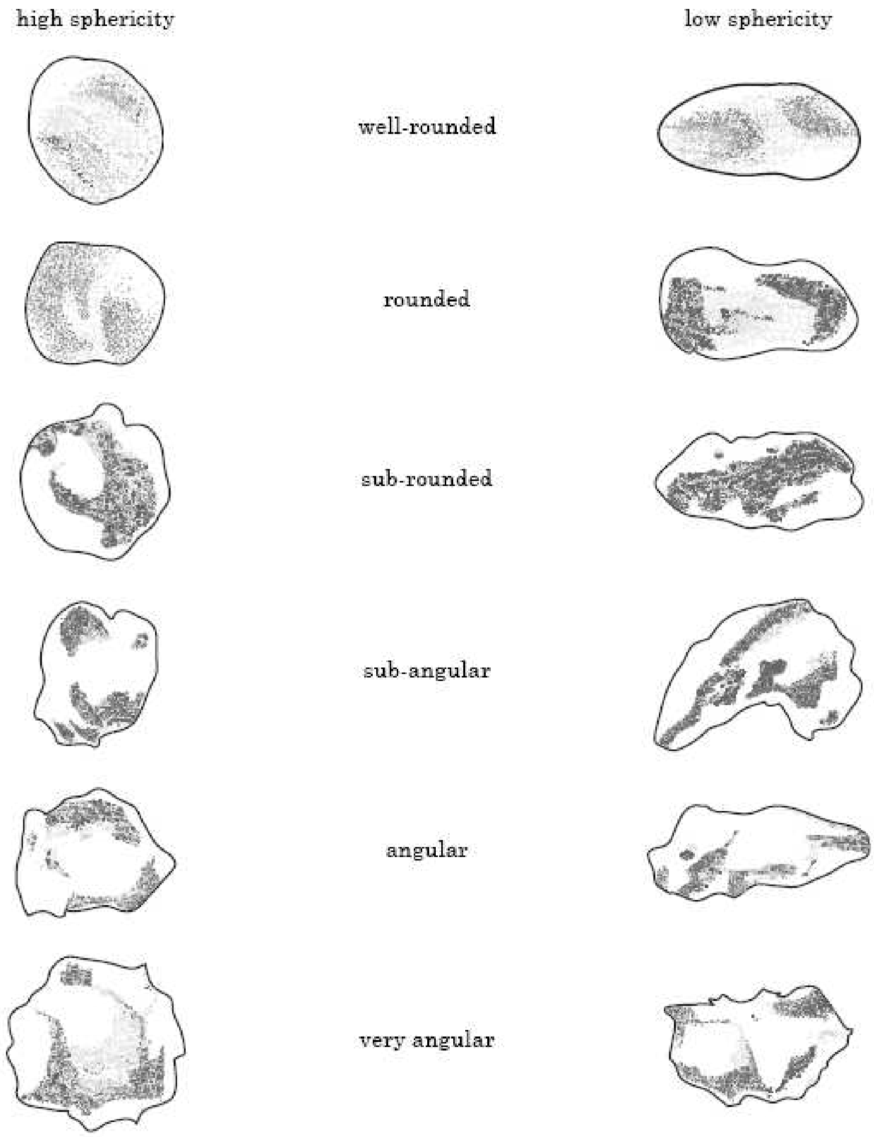


Figure 4.1: Particle shape classification in terms of angularity and sphericity (BSI, 1999).

4.2 Laboratory investigation

Soils sampled from the debris flow source areas were taken back to the laboratory in order to quantify the material properties and to allow interpretations to be made on how they may influence the susceptibility of a hillslope to debris flow activity. The experimental programme was designed to allow classification of the hillslope materials and investigation of the effective stress parameters and permeability of the soils. All the tests in the laboratory investigation were carried out on the matrix of the sampled regoliths (particles < 2mm in diameter). This was due to the fact that all the sampled hillslope were observed to be matrix dominated (so that particles larger than 2 mm were entirely supported within the matrix) and therefore properties such as the shear strength and permeability of the soil are determined by the < 2mm fraction (Innes, 1982; Ballantyne, 1986; Fannin *et al*. 2005).

4.2.1 Soil Classification

The sampled regolith matrixes were classified based upon their particle size distribution, organic content and particle shape and texture. Particle size analysis of sampled soil was carried out using a Coulter LS250 laser granulometer. In the laser granulometer scattering from a laser beam as it passed through a specimen within a suspension is observed at multiple angles. A multi-parameter equation is then mathematically inverted to determine the particle size distribution has produced the observed multi-angle scattering. The test specimen is prepared by being oven dried, gently ground and sieved through a 2mm sieve. The sediment is treated to remove organic matter using hydrogen peroxide (H_2O_2). 5 g of the sediment is placed into a beaker and 10 ml of water and 10 ml of hydrogen peroxide is added to each sample. The reaction is observed and if necessary the effervescence is controlled by adding a few drops of industrial methylated spirits. After 2 to 3 hours if effervescence has ceased a further 10 ml of hydrogen peroxide was added and the sample left to stand overnight. The beakers were then warmed on a hotplate (starting at 80ºC and gradually increasing the temperature to 100ºC) until reaction is complete and a clear supernatant is visible above the sample. The supernatant is carefully decanted and the remaining contents of the beaker transferred into a centrifuge bottle. 10 ml is then added and the sample centrifuged at 2500 rpm for 30 minutes. 30 ml of hexanetaphosphate is then added and the samples placed in an ultrasonic bath for 5 minutes. The samples were then placed on a magnetic stirrer and 5 – 30 ml of the sample was removed using a pipette and placed into the granulometer sample chamber for particle size analysis on the chemically-dispersed mineral fraction. Data output giving the particle diameter volume percentage is then manipulated using an excel spreadsheet to produce grain size curves for each sample. Based upon the particle size analysis, each of the samples was categorised into soil groups using the British Soil Classification System for Engineering Purposes as outlined in BS 5930 (1981) (table 4.1). This classification is used rather than a more recent system in the updated BS 5930 (1999) as the division between very silty sand and silty sand of 20% in the 1999 system compared to 15% in the 1981 system sees the vast majority of Scottish mountain soils falling into the silty sand category (BSI, 1999; Innes 1986). Therefore, the 1981 classification provides a better subdivision of the range of particle sizes commonly experienced in mountain soils allowing for more effective differentiation and conceptualisation of the coarse regolith matrixes studied in this work.

The shape of larger particles in the soil samples was visually assessed using a hand held lens to allow characterisation of particle angularity in each sample (BSI, 1999). The organic content of sampled soil was determined using the loss on ignition technique (BS 1377, 1990). The soils were then classified as either slightly organic, organic or very organic based on the percentage weight of organic material of the dry mass (BSI, 1999) (table 4.2).

Soil Group	Fines (% less than 0.06 mm)
Slightly silty sand	0 to 5
Silty sand	5 to 15
Very silty sand	15 to 35

Table 4.1: Classification of soil matrixes (BSI, 1981).

Term	Organic content	Weight % of dry mass
Slightly organic	Low organic content	2 to 6
Organic	Medium organic content	6 to 20
Very organic	High organic content	>20

Table 4.2: Classification of soils with organic components (BSI, 1999).

4.2.2 Strength parameters

Investigation of the effective strength parameters φ' and c' of soil sampled from source areas was carried out using a small direct shear box in accordance with BS 1377 (BSI, 1990) (figure 4.2). In the shear box tests, square specimens of soil 60 mm square and 25 mm high were laterally restrained and sheared along a mechanically induced horizontal plane while subjected to a load applied normal to that plane. The normal loads used in the tests ranged between 2 kPa and 13 kPa. These were selected to closely match the range of low effective stresses conditions experienced in the thin translational slides sampled in the field. A specially constructed light weight aluminium hanger (weight in grams = 657 g) was used to enable the application of these low normal loads. Soil specimens used in the shear box tests were reconstituted from disturbed, air dried samples passed through a 2 mm sieve to remove gravel and pebble sized particles. The soil was then re-saturated using de-ionised and de-aired water to match water content encountered in the field. Samples were carefully hand tamped into the shear box to a density equivalent to the *in situ* value measured at the landslide source areas. Shear box tests were carried out at a conservative rate of 0.01 mm min^{-1}, suitable for drained tests on silts (Bolton, 1979). Due to the dominance of sand sized particles and the high permeability of the sampled soil, this rate was slow enough to ensure that the tests were carried out under drained conditions.

During the test, the shearing resistance from the soil as one portion is made to slide on the other is measured at regular intervals of displacement with failure occurring when the shearing resistance reaches the maximum value which the soil can sustain (BSI, 1990). The shearing resistance was measured using a 5 kg load cell with vertical and horizontal displacement measured using Linear Voltage Displacement Transducers (LVDTs). The LVDTs and the load cell were calibrated and the relationship between its voltage output and engineering units determined. During the tests, the progress of the tests was followed on a HP VEE interface (figure 4.3). The output from the load cell and LVDTs was saved on the computer and stored in text files. Post test analysis was carried out using an excel spreadsheet.

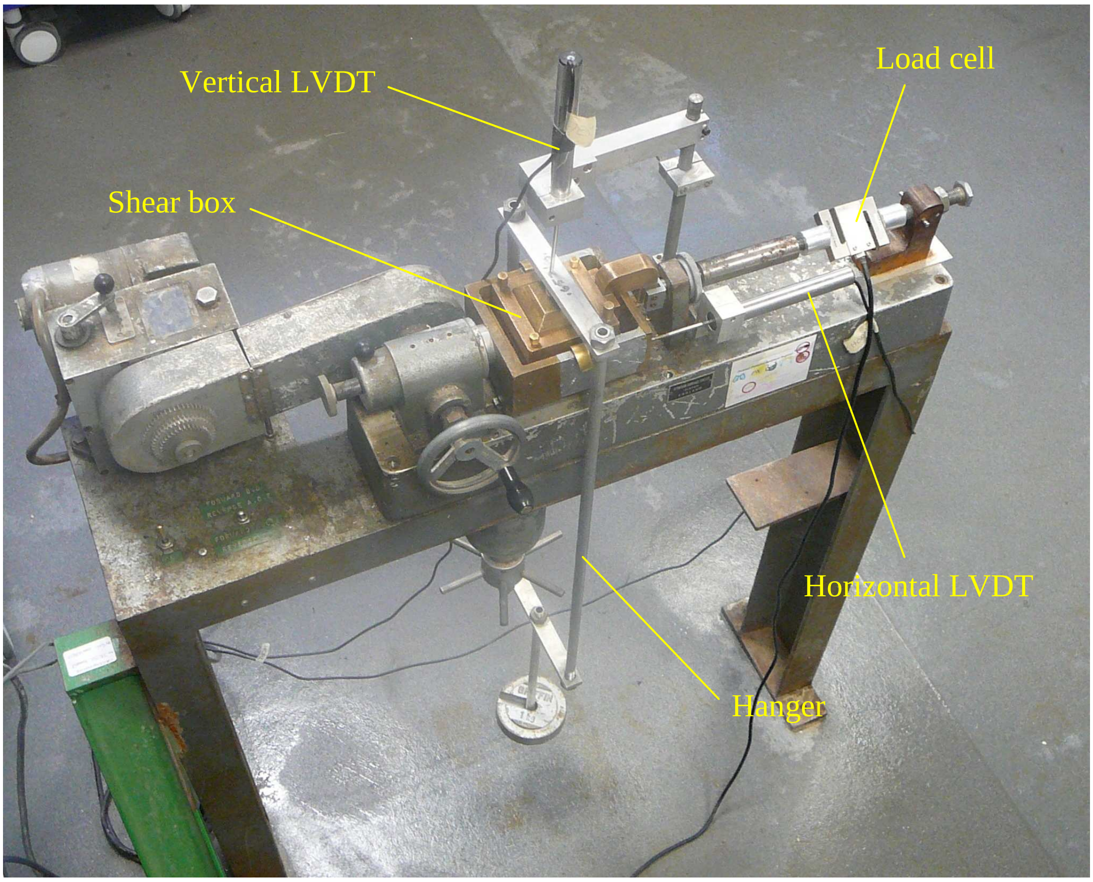


Figure 4.2: Shear box apparatus.

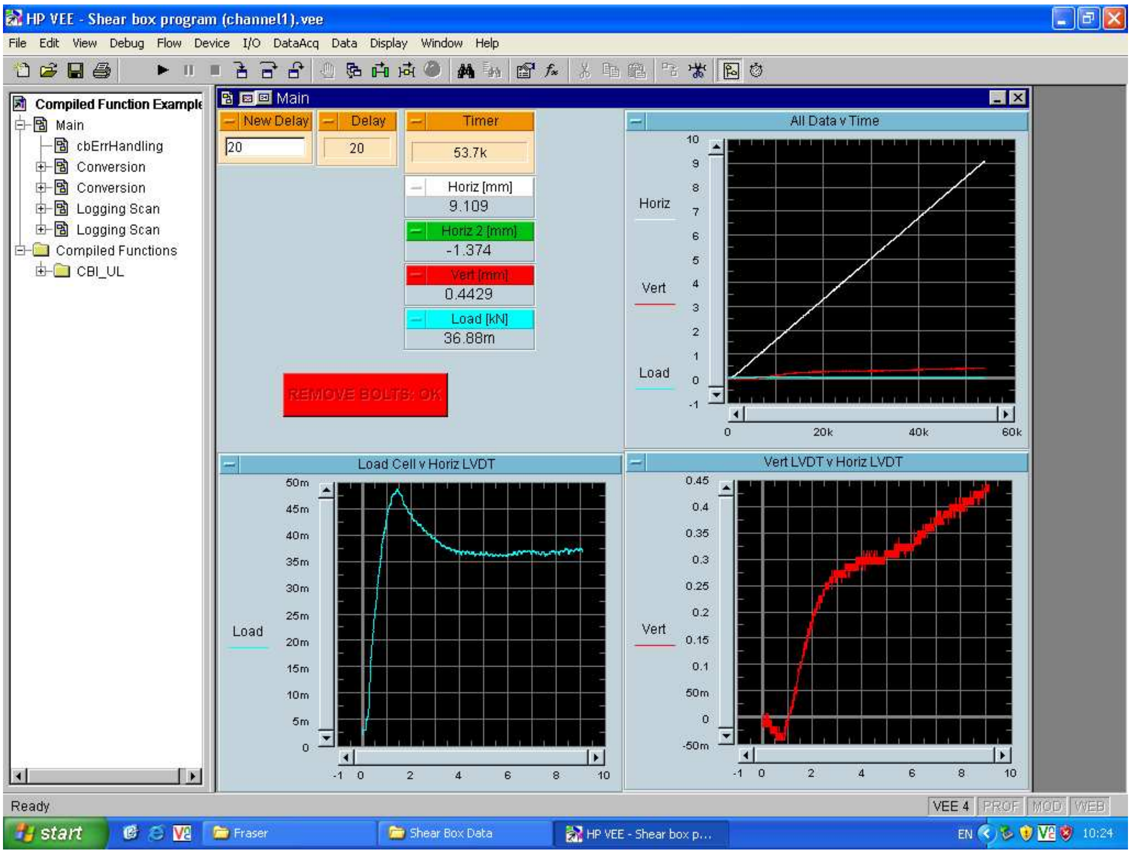


Figure 4.3: HP VEE interface used to monitor the progress of shear box tests in operation.

4.2.3 Permeability

The permeability of the soils was investigated using the constant-head permeability test following the procedures outlined in BS 1377 (BSI, 1990) on specimens of soil 51 mm diameter and 40mm high using a specially constructed permeameter cell. The cell is smaller than those normally used for permeability tests with the tests being carried out on 51 mm diameter and 40 mm high soil specimens and the hydraulic gradient measured between two manometer tubes positioned at the top and the bottom of the specimen (figure 4.4). The internal diameter of the cell is sufficient to allow for accurate determination of soil specimens as stipulated in BS 1377-4 (BSI, 1990). This permeameter cell was developed as a result of the finite supply of material available for testing caused by the remoteness and steepness of sampling areas. As with the shear box tests, the tested soil specimens were reconstituted from air dried disturbed samples. Samples were sieved through a 2 mm sieve to remove larger than sand sized particles and re-wetted using de-ionised and de-aired water to match the moisture content encountered in the field. The sample was then carefully hand tamped directly into the permeameter cell to match the density measured in the field. Hand tamping was carried out in four separate layers to maintain heterogeneity. De-ionised and de-aired water was used during the permeameter tests.

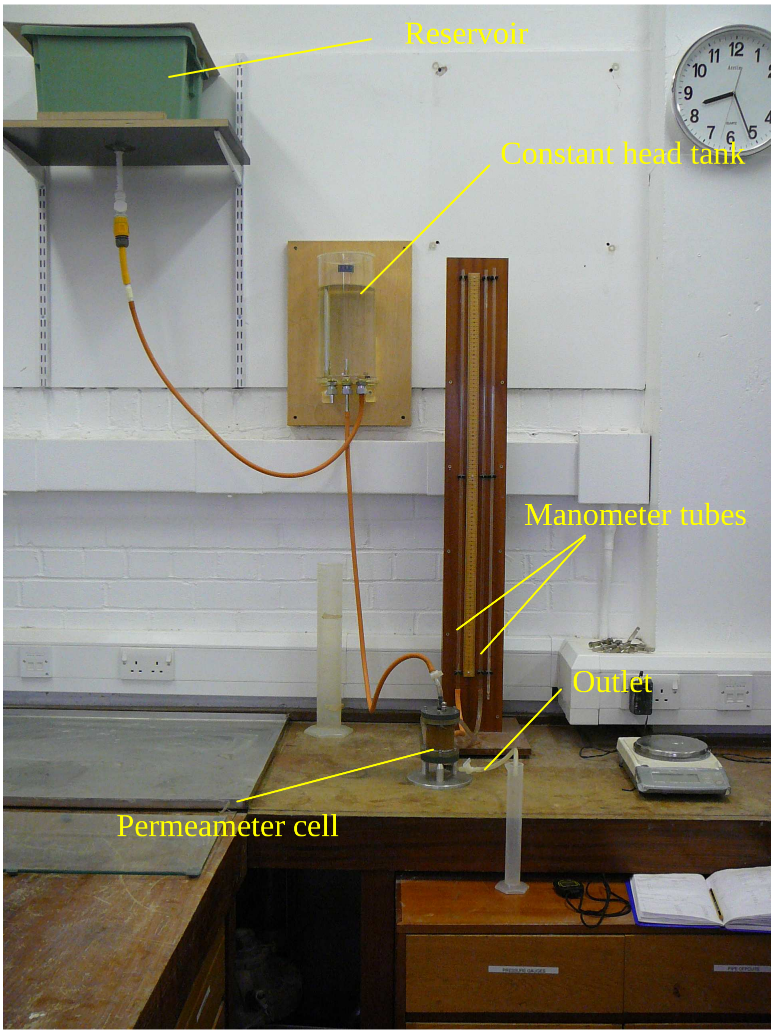


Figure 4.4: Constant permeameter test using a specially constructed small permeameter cell.

4.3 Centrifuge Modelling

A centrifuge model was developed to investigate debris flow initiation in soils with relatively coarse and fine soil textures. The primary aim of the model was to monitor the effect of particle size distribution on the susceptibility of the slope to landsliding associated with increasing phreatic surface. The principles of centrifuge modelling as well as the model development, experimental procedure and the centrifuge equipment are described in detail in chapter seven of the thesis.

5. Field Observations and Measurements

At each study site an extensive ground survey was carried out in order to investigate the site specific nature of debris flow activity. This comprised of visual site assessment, geomorphological mapping and calculation of the spatial frequency of debris flow activity. Field investigation also encompassed sampling of hillslope materials and measurement of debris flow geometry. Observations and measurements made during investigation of the debris flow process at each study site are presented in this chapter.

5.1 Debris Flow Spatial Density

The spatial frequency of debris flows at each study site was determined by dividing the number of observed debris flows by the length of the investigated slope (table 5.1). The highest debris flow densities were recorded on the granitic slopes of Glamaig and the Lairig Ghru at 32 km^{-1} and 30 km^{-1} respectively. The debris flow density at the basaltic part of Glamaig was found to be lower than the adjoining granite slopes of the mountain, with a debris flow density of 24 km^{-1}. The studied slope on the north face of Glas Mheal Mor in the An Teallach massif registered a debris flow density of 24.3 km^{-1} with 34 debris flows observed over a 1.4 km section of hillslope. The Pass of Drumochter was calculated to have a debris flow density of 18.2 km^{-1}. The study sites at Glen Ogle and Mill Glen were found to have the lowest frequencies of debris flows. At Mill Glen 6 debris flows were observed across a 1.1 km long slope, whereas at Glen Ogle 28 debris flows were recorded along 5 km of hillslope giving spatial densities of 5.5 km^{-1} and 5.6 km^{-1} respectively. At Glen Ogle a longer section of hillslope was studied than at any other site due to the occurrence of widespread debris flow activity contemporaneous with the onset of this research. The maximum spatial density for a 1 km section of slope in Glen Ogle is 10 km^{-1} whilst the minimum is 3 km^{-1}. The measured debris flow densities show a pattern in which study sites which are underlain by coarse grained granite and sandstone lithologies display the greatest spatial density of debris flows whereas those with finer grained schistose and extrusive igneous lithologies tend to have a lower frequency of debris flow landforms, particularly in the case of Glen Ogle (mica-schist) and Mill Glen (andesite).

The measured debris flow densities were normalised for the effect of varying rainfall at each study site using the 30 year mean annual rainfall (1961 -1990) (table 5.2). After normalisation, the highest debris flow density is at the Lairig Ghru, with the granite part of Glamaig displaying the second highest spatial frequency despite the high average annual rainfall total at this study site. The high rainfall total at An Teallach results in a normalised spatial density of 9.8 km^{-1}, lower than the spatial density at the Drumochter Pass (10.1 km^{-1}). The lowest normalised spatial debris flow density is at Glen Ogle (2.9 km^{-1}) which has a slightly lower spatial frequency than Mill Glen (3.3 km^{-1}) on account of a higher average annual rainfall. The sites underlain by coarse grained lithologies investigated in this research generally experience higher rainfall totals than the study sites characterised by fine grained bedrock. Therefore, the coarse grained study sites at An Teallach, Glamaig (granite) and the Lairig Ghru experience greater reductions in debris flow density during normalisation. In spite of this, a generic trend in which slopes underlain by coarse grained lithologies are seen to yield a greater number of debris flows than slopes underlain by finer grained lithologies endures after normalisation with rainfall totals (figure 5.1; table 5.2).

Study site	**Geology**	**Number of debris flows**	**Length of slope** (km)	**Debris flow density** (km^{-1})
An Teallach	Torridonian Sandstone	34	1.4	24.3
Glamaig (basalt)	Basalt	24	1	24
Glamaig (granite)	Granite	32	1	32
Lairig Ghru	Granite	27	0.9	30
Drumochter Pass	Psammitic schist	31	1.7	18.2
Glen Ogle	Mica-schist	29	5	5.8
Mill Glen	Andesite	6	1.1	5.5

Table 5.1: Spatial density of debris flows at each study site.

Study site	**Mean annual rainfall** (1961 -1990)	**Actual debris flow spatial density** (km-1)	**Normalised debris flow spatial density (km^{-1}/m a^{-1})**
An Teallach	2.489 m	24.3	9.8
Glamaig (basalt)	* 2.888 m	24	8.3
Glamaig (granite)	* 2.888 m	32	11.1
Lairig Ghru	2.038 m	30	14.7
Drumochter Pass	1.797 m	18.2	10.1
Glen Ogle	1.978 m	5.8	2.9
Mill Glen	1.648 m	5.5	3.3

Table 5.2: Normalised spatial density at each study site (* proxy data from Sgurr Na Coinnich, 25 km ESE of Glamaig).

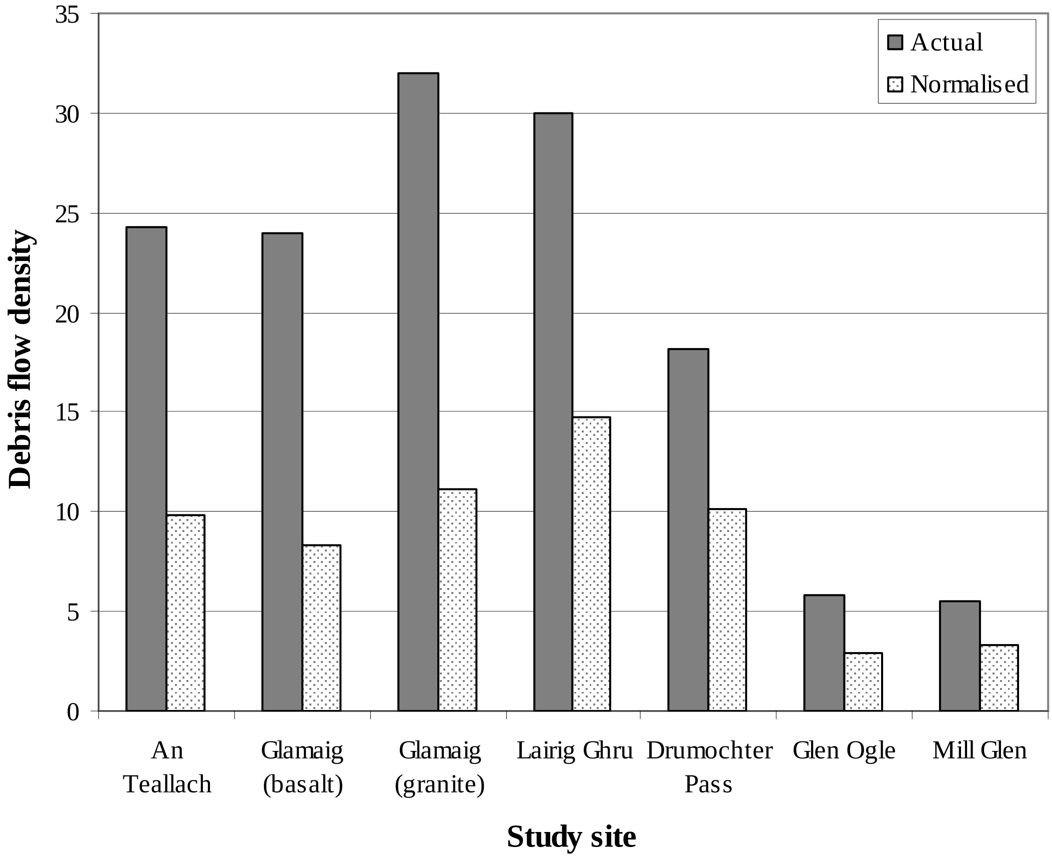


Figure 5.1: Actual (measured) debris flow spatial densities and normalised debris flow spatial densities for mean annual rainfall (1961-1990) at each study site.

5.2 Site Investigations

5.2.1 An Teallach

A total of 22 individual debris flows were observed at the An Teallach study site (figure 5.2). At the eastern side of the study site 6 debris flows were identified on a relict talus slope below a rock head. On the upper slopes above this cliff there is evidence of the reworking of frost shattered detritus by debris flow activity in the form of 4 hillslope debris flows. Towards the eastern end of the study site there is less exposed bedrock and the frost shattered detritus extends further down slope. Debris flows on these slopes comprise of long, narrow hillslope debris flows with debris tracks approximately 2 to 5 m wide, forming levees and narrow debris lobes up to 7m wide. Debris tracks are identified by the presence of narrow grassed surfaces on the sparsely vegetated hillslope, marking the deposition of finer grained material by debris flow (figure 5.3). In some cases shallow drift cut gullies (less than 1m deep) have been formed by this debris flow activity.

The bouldery terminal lobes and levee deposits in all of the debris flows at the An Teallach study site are vegetated to varying degrees. In previous research, debris flow lobe deposits dating from 1978 at the Drumochter Pass and 1985 in the Lomond hills of Fife, were observed to have become entirely covered with vegetation by within 20 and 10 years respectively (Curry, 2000a). The distribution of debris flows observed at the An Teallach study site is also broadly similar to that mapped by Ballantyne in 1981 (Ballantyne, 1981). Consequently, a period of inactivity greater than 10 to 20 years can be assumed for the An Teallach study site.

Two debris flows were examined in closer detail at the study site. These are termed An Teallach 1 and An Teallach 2 (figure 5.2; figure 5.4). The source area of An Teallach 1 (AT 1) is located in a hillslope concavity approximately 0.5 m deep and 10 m wide on a open slope with a gradient of 36º immediately below exposed crags. The altitude of the source area is approximately 680 mAOD. A landslide scar within the source area was measured as approximately 4 metres wide and 12 metres long. Investigation of the headscar of this landslide revealed that the failure plane existed at a depth of approximately 0.3 m within a 0.82 m thick mantle of uniformly graded red-brown sand with the occasional pebble to cobble sized angular clast (figure 5.5a). This indicates that debris flow generation took the form of a very shallow translational slide involving approximately 13.2 m^2 of material. The uniformly graded nature of the regolith is indicative of the niveo-aeolian genesis of the material, in which sand eroded from adjacent plateaux was blown on to snow cover and then deposited onto the slope following snow melt (Ballantyne & Morrocco, 2006). The upper 0.18 m of the profile has a high density of grass roots some of which extend deeper into the soil profile. The sandy mantle overlies a surface of angular, cobble sized clasts which represent the buried surface of a relict talus slope. The density of the sandy material encountered at the headscar was found to be 1.54 Mg m^{-3} with the water content at the time of sampling 9.4%. After initiation, the debris flow passed over an open hillslope with a slightly concave profile and an average gradient of 30.7° before terminating on a slope with a gradient of 21-22° (figure 5.6a). The overall length of the debris flow from the headscar to the terminus is approximately 103 m. The debris track is approximately 5 metres wide and is flanked for the lower 35 m by levees up to 0.45 m high. The deposited debris form a lobe approximately 6.7 m wide, 16 m long and 0.55 m deep which is deflected to the west by a Loch Lomond Stadial terminal moraine (figure 5.2). The approximate volume of material in the lobe is 59 m^3, indicating that a greater volume of material is deposited in the lobe than was involved in the landslide measured at the source area. There is also a significant volume of material deposited in the levees that flank the debris track. The absence of a drift cut gully suggests there was little or no accumulation of material from hillslope erosion during flow propagation. Therefore, it is apparent that the lobe at AT 1 is the product of several debris flows generated by translational sliding in the source area. Boulders up to 0.85 m in diameter were measured amongst the largest particles in the debris deposits at AT 1, although the measured deposits were dominated by cobble sized particles. Particles were sub-angular to angular in shape (figure 5.7a).

The An Teallach 2 (AT 2) debris flow is located on the relict talus slope below the rock head at the eastern side of the study site (figure 5.4). The debris flow is approximately 135 m long and has propagated through a gully up to 2.4 metres deep and 6.6 metres wide incised into the relict talus slope (mean gradient 34.5°) (figure 5.6b). The presence of a small stream suggests that the gully is at least partially fluvial in genesis with incision possibly enhanced by debris flow activity. The walls and the majority of the gully floor are completely vegetated indicating a period of stability of at least 10 to 20 years (Curry, 2000a). The source area of the debris flow is located at the head of the gully at the base of a rock head on a slope with a gradient of 36.5°. An elongate 25 m by 4 m wide scar in the source area marks the occurrence of a translational landslide. Analysis of the headscar revealed a 0.63 m deep uniformly graded red-brown niveo-aeolian sand deposit similar to that observed at AT 1 (figure 5.5b). The failure plane is located low in the profile apparently corresponding with the interface between the overlying regolith and the underlying relict talus. The density of the regolith at the AT 2 headscar was measured as 1.53 Mg m^{-3} with a water content of 6.3%. The debris flow follows the floor of the gully until the gully dissipates at the toe of the talus slope. The debris flow then propagates over the open hillslope for approximately 47 m flanked by levees up to 0.6 m high before terminating on a gradient of 20° forming a lobe 7.6 m wide, 16.9 m long and approximately 0.7 m high. The approximate volume of material in the terminal flow lobe is 90 m^3 whereas the initiating landslide involved approximately 63 m^3. In addition the levees are estimated to contain up to 70 m^3 of material. The greater volume of material in the debris deposits suggests the accumulation of material from several debris flows and/or the entrainment of excess debris from the gully during the propagation phase of the flow. Boulders up to 0.61 m in diameter were measured amongst the largest particles in the debris deposits at AT 2 although, as at AT 1, the measured deposits were dominated by cobble sized particles. Particles were sub-angular to angular in shape (figure 5.7b).

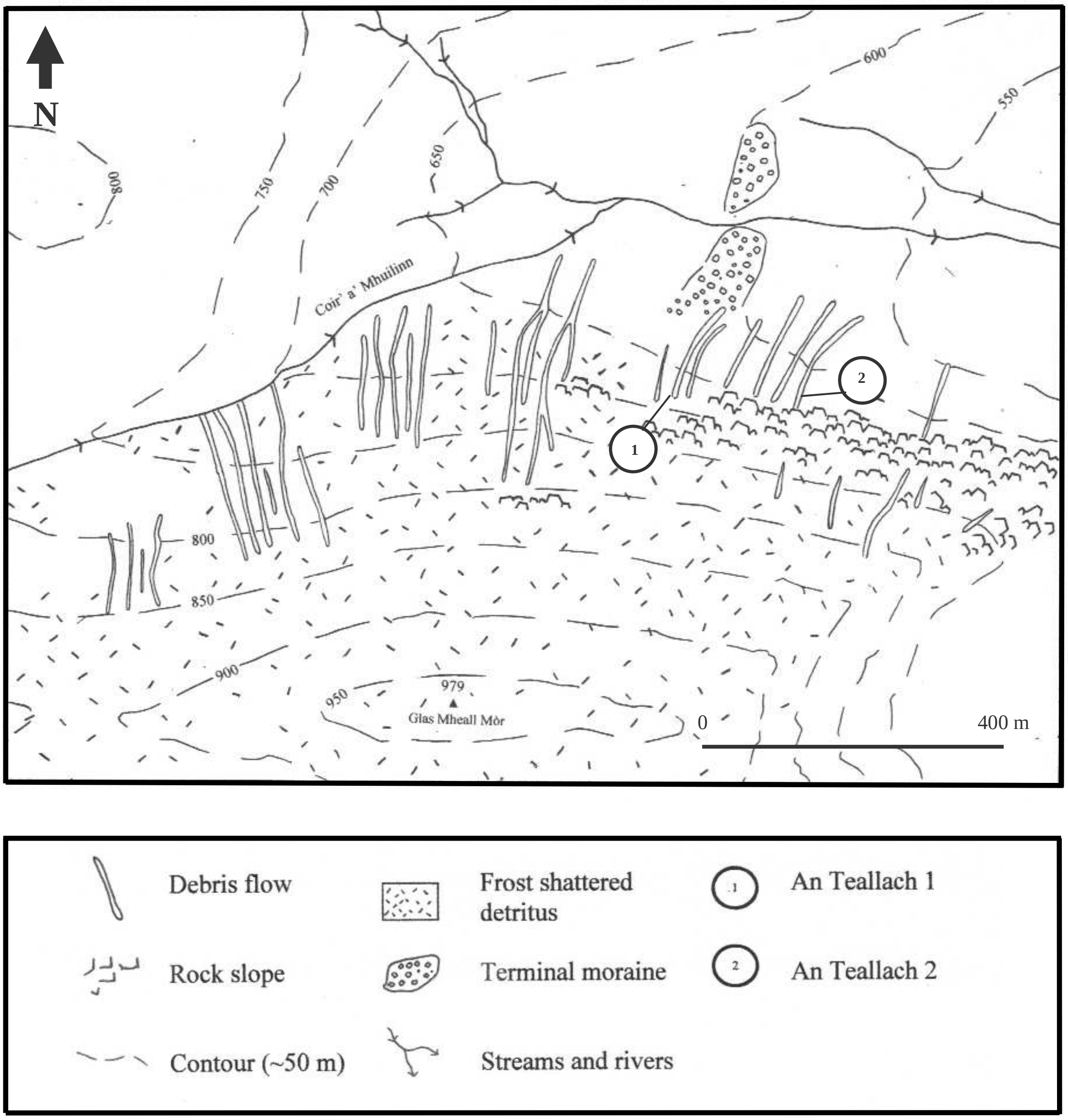


Figure 5.2: Geomorphological map of the An Teallach study site.

Figure 5.3: Narrow grassed surfaces on the sparsely vegetated debris slope, marking the deposition of finer grained material in debris flow tracks.

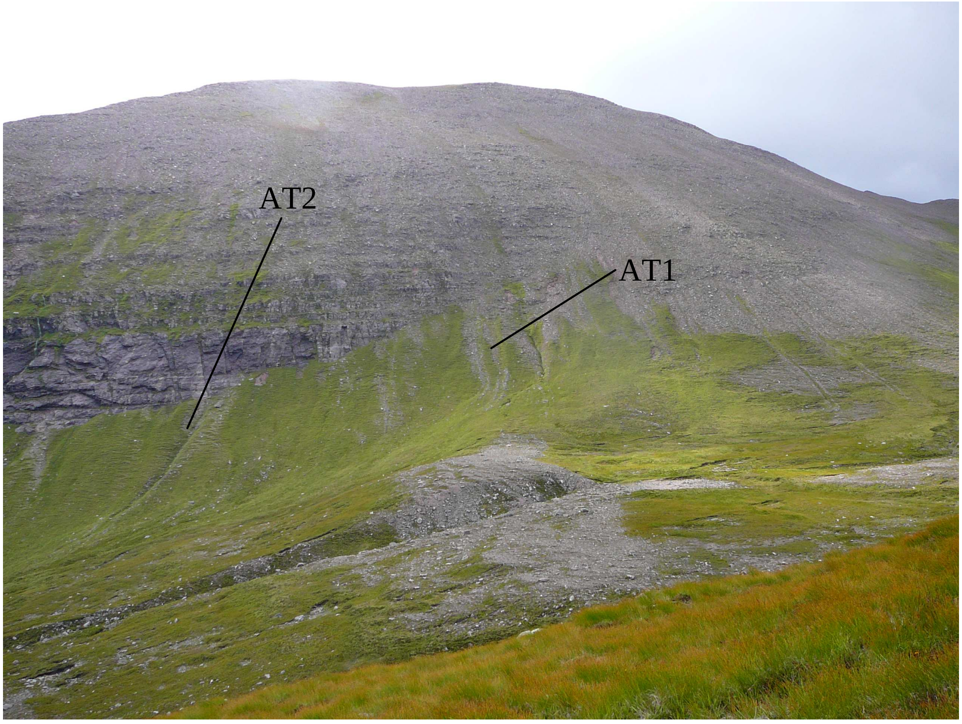


Figure 5.4: Overview of An Teallach 1 (AT1) and An Teallach 2 (AT2) debris flows.

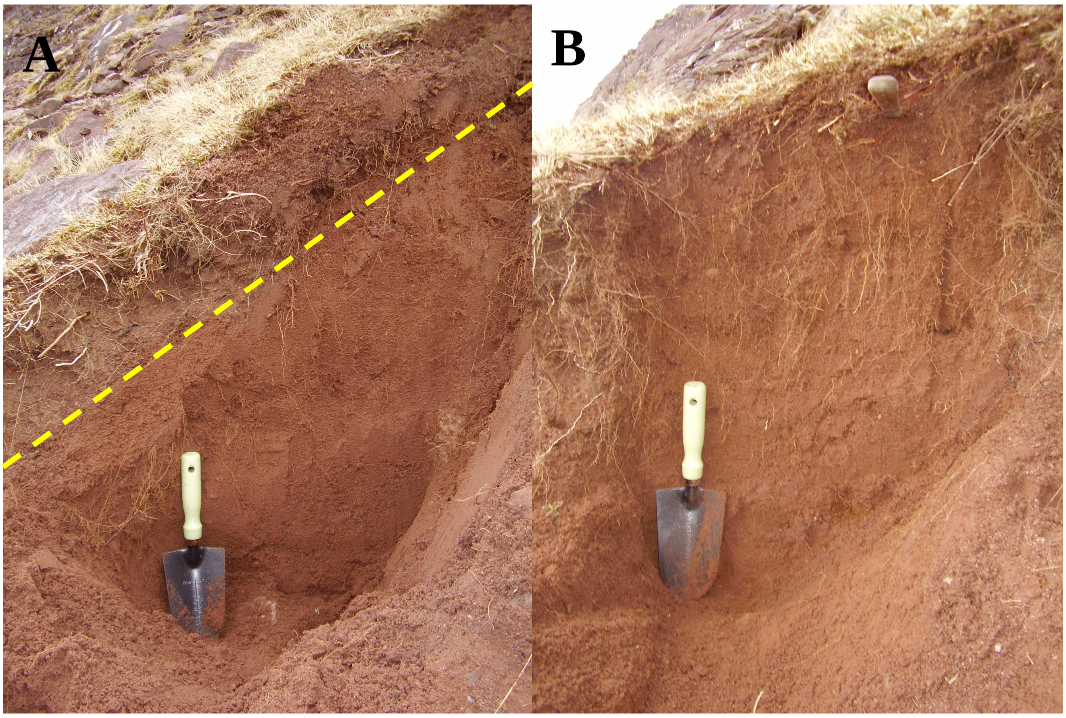


Figure 5.5: The soil profile at the source area of An Teallach 1 (a) and An Teallach 2 (b). The position of the failure plane in the An Teallach 1 profile is marked by the dashed line.

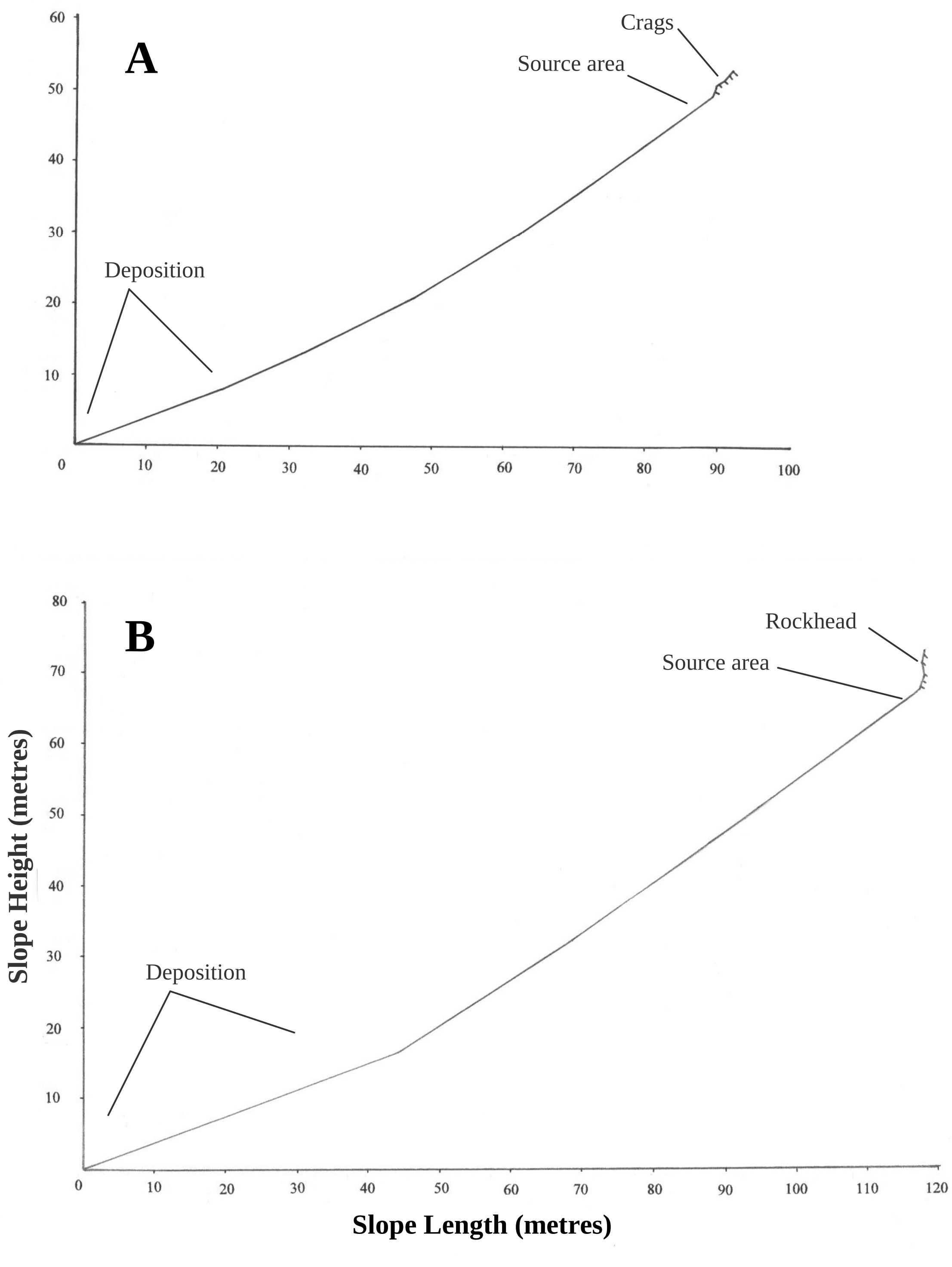


Figure 5.6: Slope profiles for the An Teallach 1 (A) and An Teallach 2 (B) sampled debris flows.

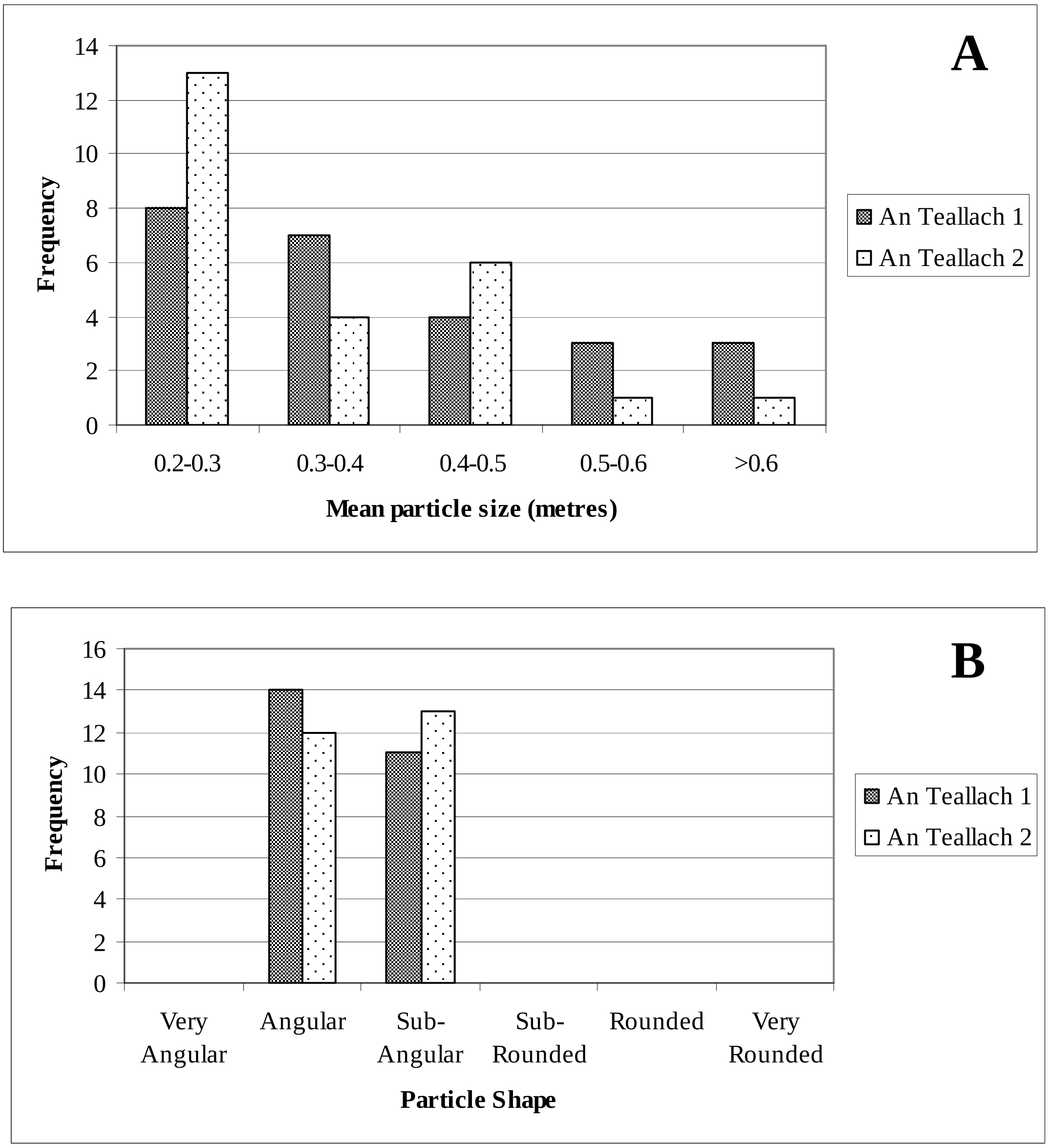


Figure 5.7: Mean particle size (a) and shape (b) frequency distributions of the largest particles in the debris deposits at An Teallach 1 and An Teallach 2.

5.2.2 Glamaig

A high density of debris flows was observed at the Glamaig study site with a total of 24 and 32 debris flows identified on the basaltic and granitic aspects of the mountain respectively (figure 5.8). The high spatial frequency of debris flows at the site is highlighted by expanses of exposed regolith on the mountain side which delimit debris flow routes sparsely interrupted by strips of unscarred vegetated slopes (figure 5.9). This exposed material is periodically reworked by debris flow activity evident from the presence of parallel levees and fresh deposits on the exposed debris slopes (figure 5.10). The source areas of many of the debris flows tend to occur in or immediately downslope of gullies and couloirs amongst the crags and rock heads that fringe the upper slopes of the mountain. As a consequence of the high spatial frequency of debris flows at the site, the foot of the slope is carpeted with debris flow deposits and incipient debris cones. Debris flow deposits were observed to be thicker on the granite side of the mountain. This suggests that debris flows on the slopes underlain by granite may tend to be of a greater magnitude and/or have a higher temporal frequency compared to debris flows on the basalt side of the mountain.

Two debris flows were investigated in closer detail at the study site, one occurring in regolith mantling the basalt bedrock, Glamaig (basalt), and a second in regolith developed over granite bedrock, Glamaig (granite) (figure 5.8). Glamaig (basalt) is a hillslope debris flow which has spread over a 158 m length of hillside (figure 5.11; figure 5.12a). The upper 67 m of the debris flow comprises exposed talus approximately 9 m across on a rectilinear slope (gradient 31º) flanked by a 0.3 m thick exposure of well graded silty sand. This exposure is showing signs of being actively eroded with ravelling occurring along its length (figure 5.13). Regolith was sampled approximately 30 m below the rocky outcrop that delimits the top of the debris flow. The density of the soil sampled at this location was found to be 1.15 Mg m^{-3} with a water content of 34.4%. The regolith is black in colour indicating a high organic content (BSI, 1999). The debris flow terminates at the foot of the slope as a thin debris fan consisting of three separate debris tongues across an area approximately 13 m and 21 m long (figure 5.11). Particles up to 0.43 metres in diameter were observed in the debris deposits which were mostly comprised of very angular basalt clasts (figure 5.14a). Analysis of the sediment budget of the Glamaig (basalt) debris flow shows that the volume of material measured in the flow deposits (*c*. 183 m^3) is approximately equivalent to the volume of material eroded from the debris flow source area (*c*. 180 m^3) indicating that there has been no accumulation of material during propagation.

Glamaig (granite) is a 231 m long hillslope debris flow situated on the east facing side of the mountain (figure 5.8). The upper 156 m of the debris flow is comprised of exposed granitic debris up to *c*. 10 m across on slopes 33.5 -35.5º steep figure 5.12b; figure 5.15). As at Glamaig (basalt) the exposed debris track is flanked by a thin (*c*. 0.3 – 0.4 m) exposure of well graded organic silty sand which is experiencing active small scale ravelling erosion (figure 5.16). Soil was sampled from this exposure in the highest part of the debris flow situated approximately 480 mAOD. The density of the soil in the exposure was measured as 1.57 Mg m^{-3} with a moisture content of 36.9%. The debris flow terminates mid-way down the east facing slope of Glamaig where the gradient decreases from 32º to 27.5º forming a terminal flow lobe 13.3 m wide, 39 m long and 0.7 - 0.8 m deep (figure 5.15). The debris deposits were largely comprised of cobble to boulder sized angular particles up to 0.48 m in diameter (figure 5.14b). The volume of the debris flow deposits at Glamaig (granite) amounts to approximately 731 m^3 whereas the total volume of material removed from the source area is *c*. 546 m^3. Consequently, the sediment budget suggests that up to 185 m^3 of material has accumulated during debris flow propagation although a significant proportion of the excess material in the Glamaig (granite) debris lobe is likely to have been deposited from a small tributary debris flow adjoining the Glamaig (granite) debris flow (figure 5.15).

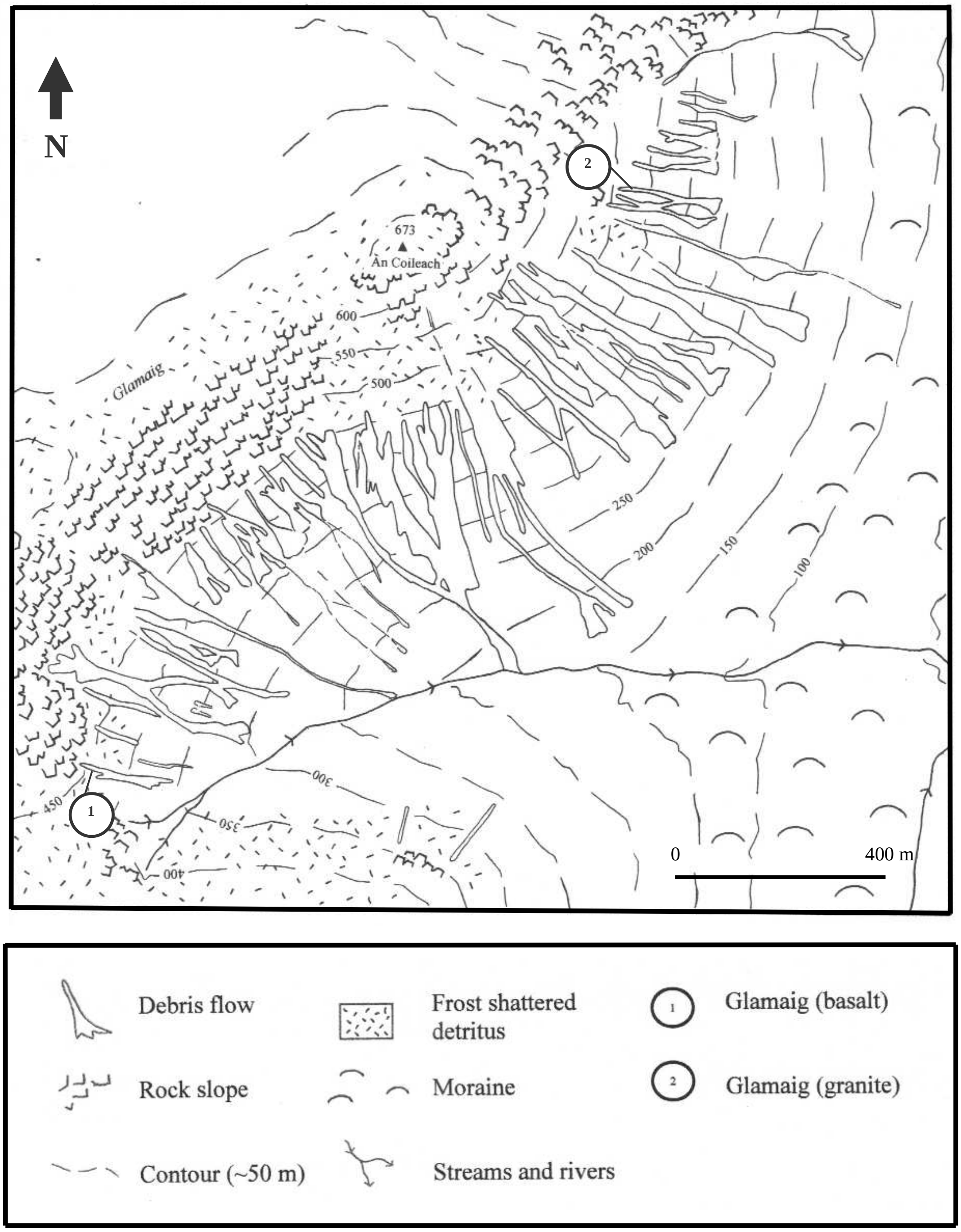


Figure 5.8: Geomorphological map of the Glamaig study site.

Figure 5.9: Photograph showing exposed regolith on the flanks of Glamaig delimiting debris flow routes.

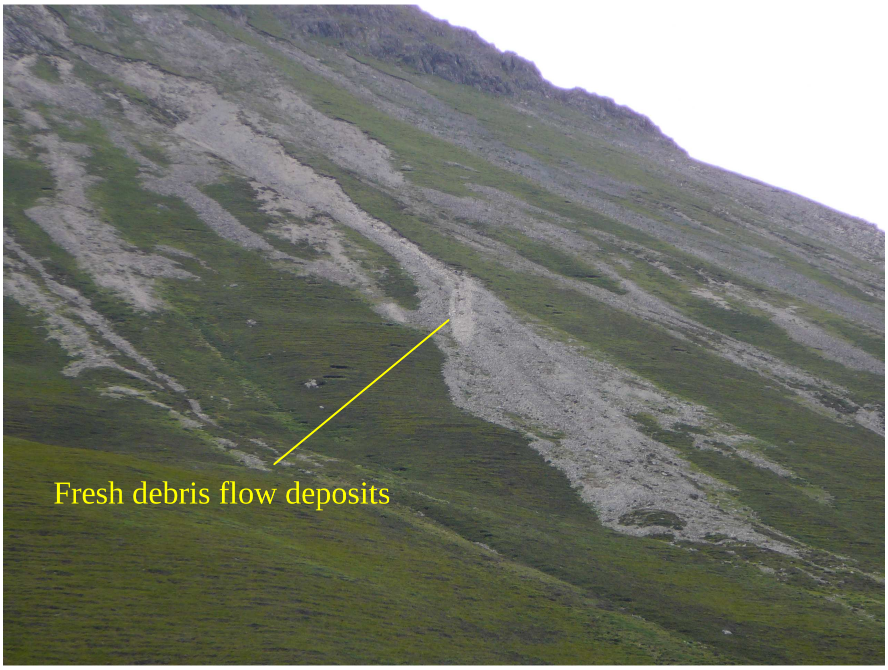


Figure 5.10: Fresh debris flow deposits on exposed regolith indicating recent flow activity.

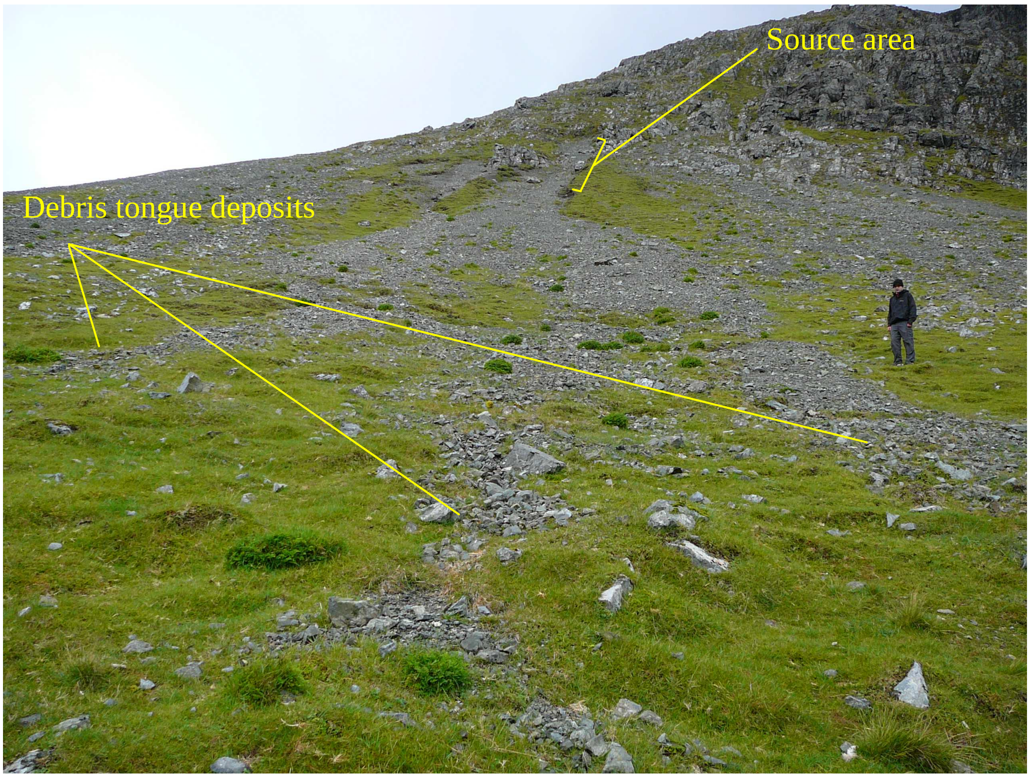


Figure 5.11: Glamaig (basalt) sampled debris flow.

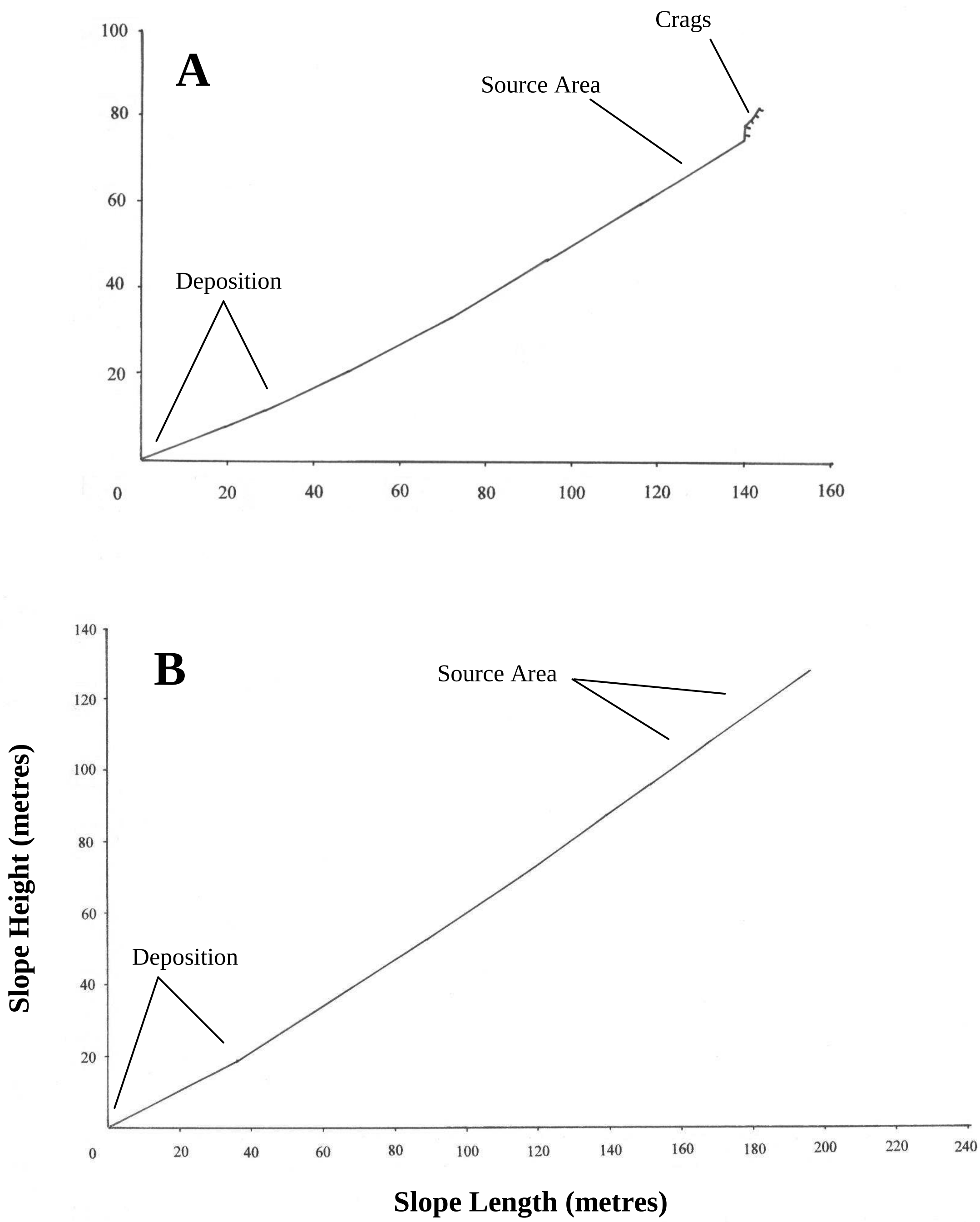
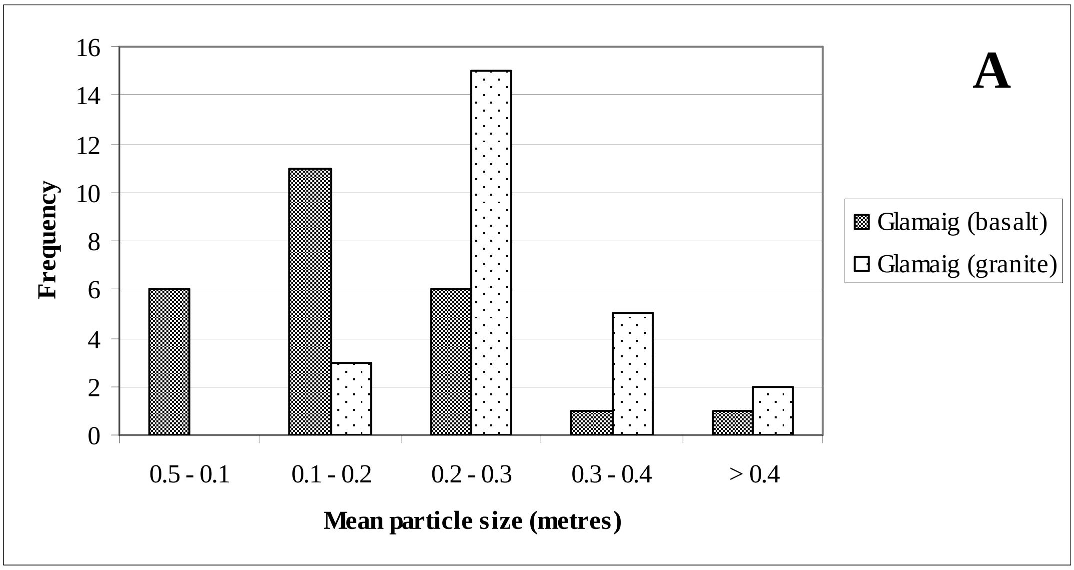


Figure 5.12: Slope profiles of the sampled debris flows on the basaltic (A) and granitic (B) sides of Glamaig.

Figure 5.13: Ravelling along exposure in upper part of the Glamaig (basalt) debris flow.



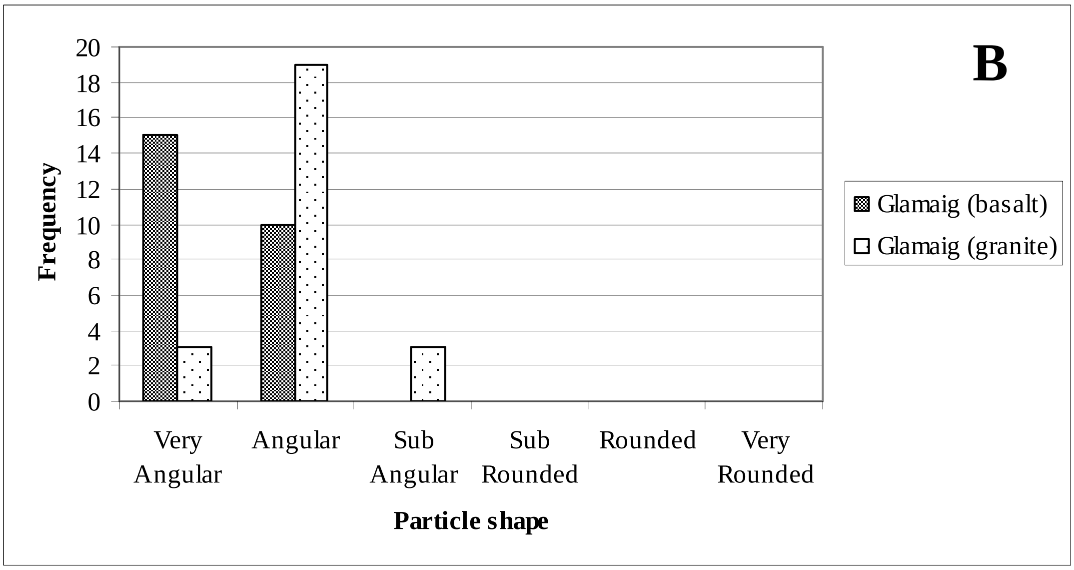


Figure 5.14: Mean particle size frequency distribution of the largest particles in the debris deposits at (a) Glamaig 1 and (b) Glamaig 2.

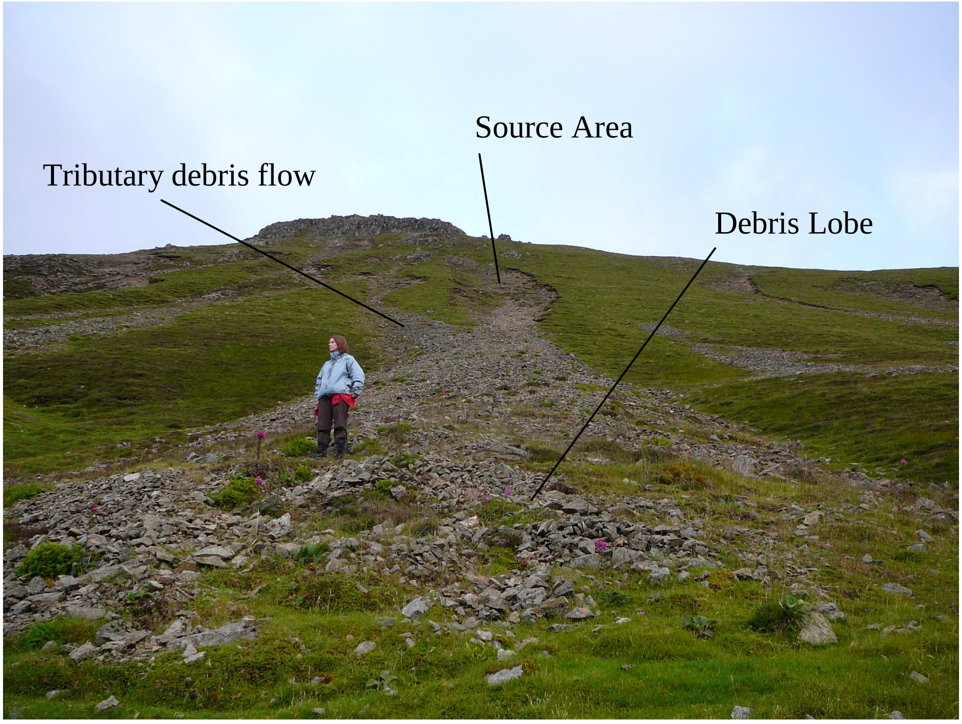


Figure 5.15: The Glamaig (granite) sampled debris flow.

Figure 5.16: Source area of the Glamaig (granite) sampled debris flow looking downslope from headscar showing ravelling of exposure.

5.2.3 Lairig Ghru

There is a high spatial frequency of debris flows at the Lairig Ghru study site with 26 separate debris flows discerned during this research (figure 5.17). Debris flows extend down the slope from altitudes of approximately 900 mAOD down to the floor of the Lairig at altitudes of 720 – 750 mAOD. The debris flows at the Lairig Ghru study site are mostly of the hillslope debris flow typology. However, in several cases the debris flow source areas exist in bedrock gullies and/or have incised gullies up to 2 metres deep into the regolith mantled slopes and can therefore be regarded as transitional between hillslope and channelised debris flows. As at Glamaig, the occurrence of strips of unscarred vegetated slopes between debris tracks indicates that debris flow activity is more likely to follow the route of established debris tracks. This encourages localised erosion and gully formation (figure 5.18). The location of debris flows on the slope is heavily influenced by the distribution of the source areas which correspond with gullies, concavities and couloirs amongst the rocky crags and outcrops in the upper slopes of the study site. Debris flow deposits from successive debris flows at the base of established debris tracks form incipient debris cones at several locations at the study site and the foot of the slope is widely carpeted with deposits in places forming levees up to 1 m in height. Some of the debris flow deposits are fully or partially vegetated whereas others have a fresher unvegetated appearance indicating varying ages of deposition. The debris lobe and levees of a debris flow mapped as "recent" by Luckman in June 1980 (Luckman, 1992) were observed to have become almost fully vegetated during the initial field visits for this research in the summer of 2005. However, further up the debris track there are some fresh, unvegetated deposits possibly indicating reworking of material by more recent, smaller scale debris flow activity.

One debris flow at the Lairig Ghru study site was sampled for closer analysis of the material and geometric controls on the debris flow process (figure 5.17; figure 5.19). The sampled debris flow has incised a gully up to 2 m deep and 11.5 m wide into the well graded, sandy regolith mantling the hillslope. The debris flow is 385 m long from the headscar to the terminus. The debris track is confined within the drift-cut gully for 174 m (figure 5.20). The source area of the debris flow occurs in a shallow hillslope concavity on a slope with a gradient of 35.5° amongst rock outcrops approximately 900 mAOD. The source area is marked by a landslide scar 48.5 m long and 15 m wide. The headscar of the debris flow exposed a 0.42 m profile of angular gravel to cobble sized granite clasts held in a matrix of coarse red-brown sand down to weathered granite bedrock (figure 5.21). The density of regolith sampled at the headscar was found to be 1.06 Mg m^{-3}, with a moisture content of 14.1%. Failure appears to have occurred low in the profile close to the interface with the bedrock leaving a thin mantle of regolith over the underlying weathered granite. Several islands of turf occur in the source area which may represent the remnants of a vegetation mat left behind after the apparent liquefaction of a translational landslide. The gully incised into the slope by the debris flow commences immediately downslope of the source area. The steep and unvegetated gully walls are vulnerable to slope wash and slumping into the gully providing an abundant supply of unconsolidated, exposed material on the gully floor. The floor of the gully is also persistently steep with gradients up to 34.5°. This combination of a steep gradient and abundant supply of unconsolidated material results in a high potential for reworking of gully floor sediment by debris flow activity. The debris flow terminates as a debris lobe 9.8 m wide and 0.63 m thick on a gradient of 11°. However, deposits from the debris flow cover an area approximately 34 m across forming several other debris tongues and forming levees up to 0.66m high (figure 5.19). The fresher deposits overlie older, vegetated debris flow deposits sourced from the same debris track, together forming an insipient debris cone. The largest clasts in the debris flow deposits consist of sub-angular to very angular granitic boulders with a mean diameter of up to 0.71 m (figure 5.22). The insipient debris cone was estimated to contain approximately 1530 m^3 of material whereas the total volume of material evacuated from the source area is *c*. 306 m^3. Consequently, the majority of material deposited at the slope foot is sourced from material eroded from the drift-cut gully.

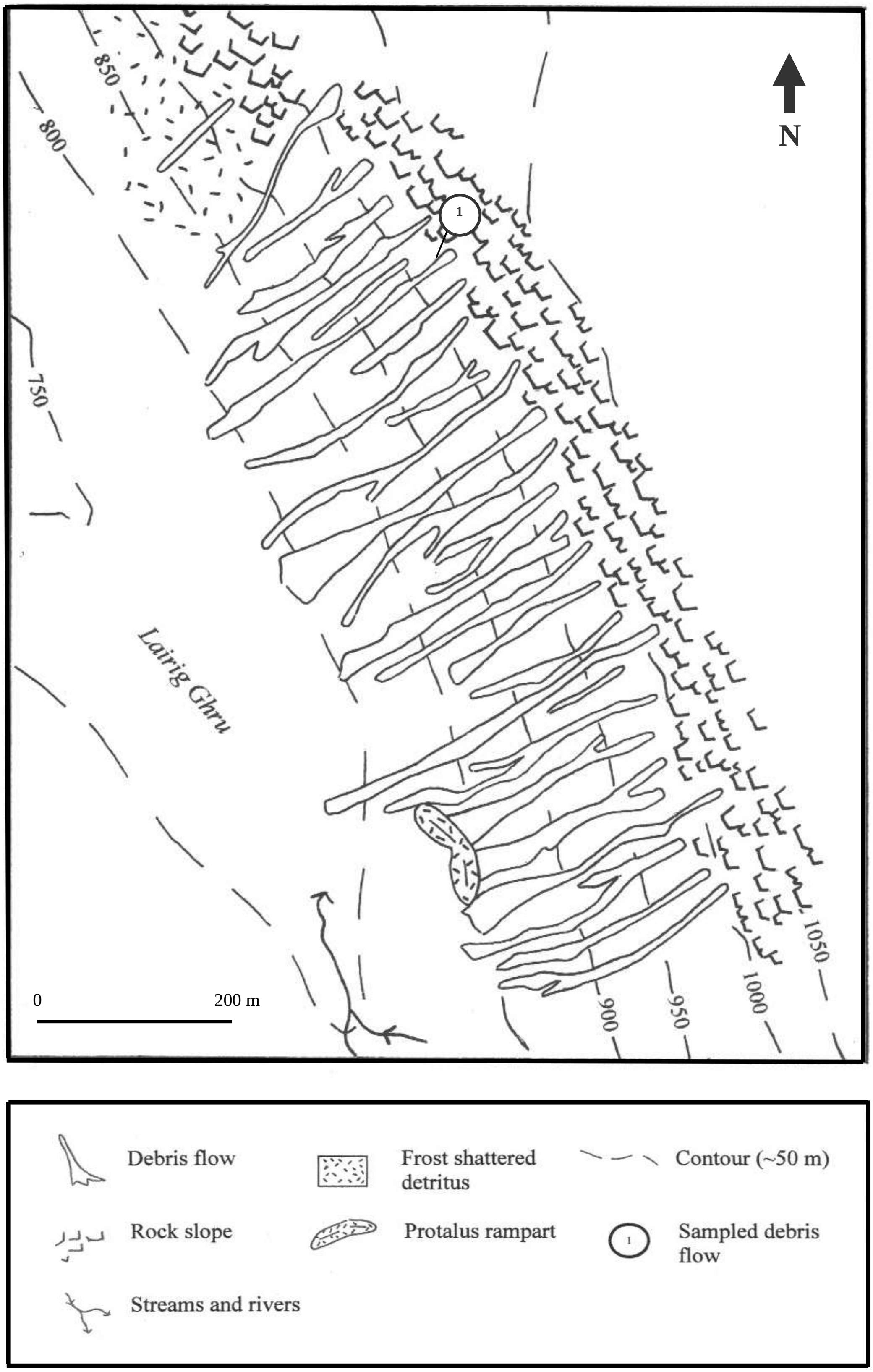


Figure 5.17: Geomorphological map of the Lairig Ghru study site.

Figure 5.18: Debris tracks in the Lairig Ghru study site.

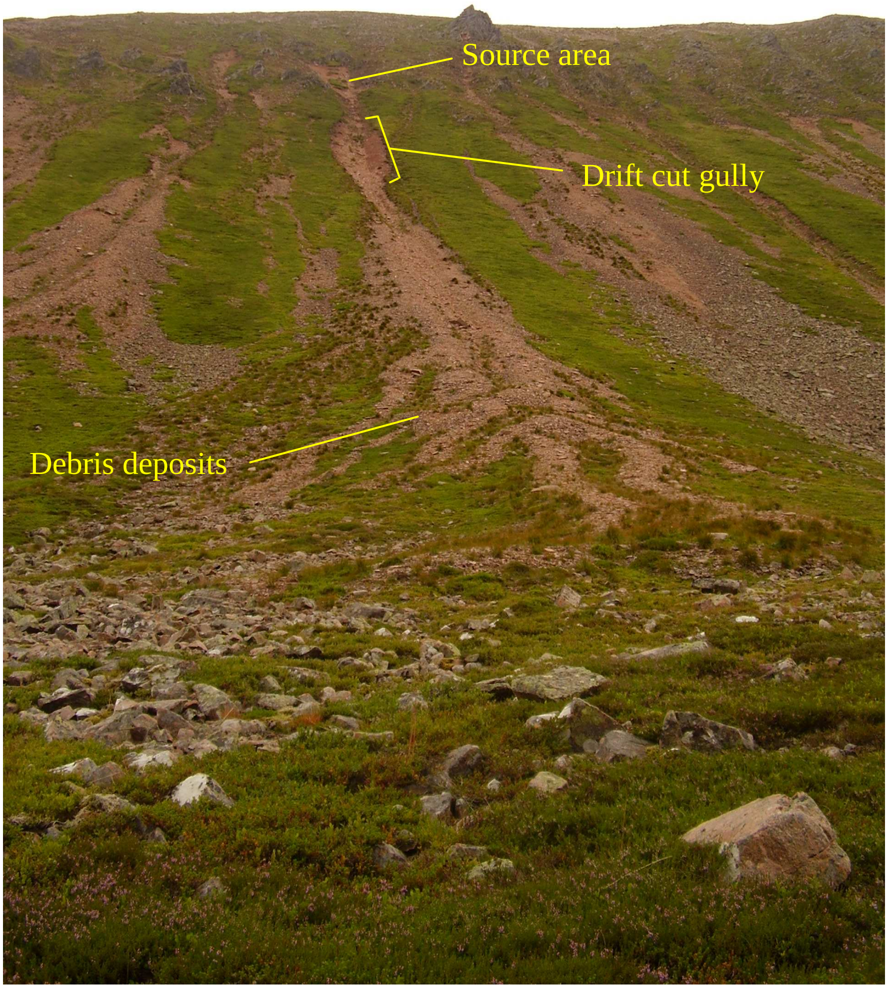


Figure 5.19: Sampled debris flow at the Lairig Ghru.

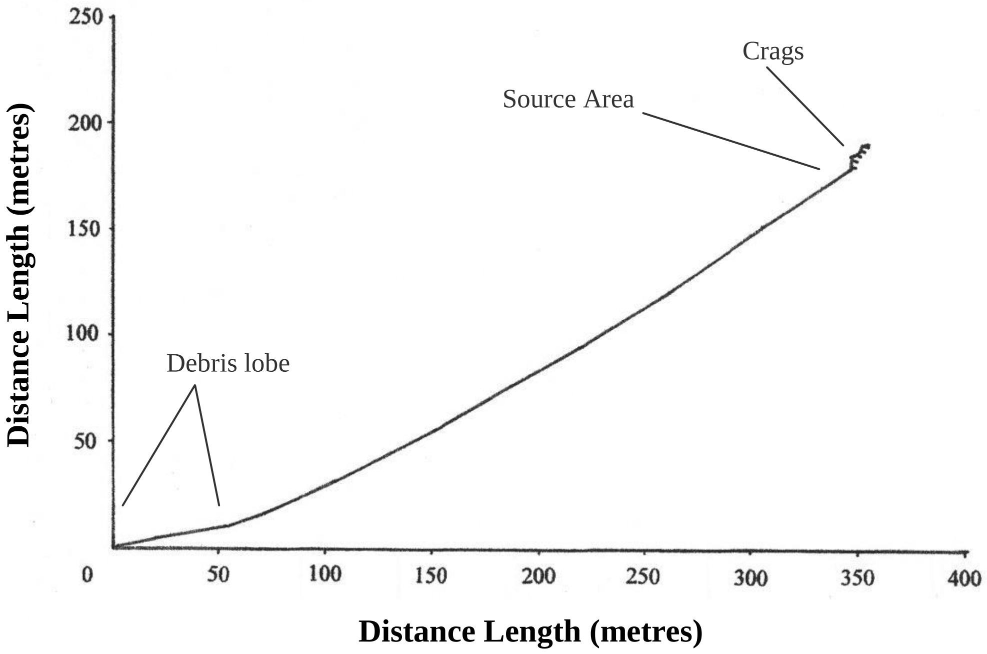


Figure 5.20: Profile of sampled debris flow at the Lairig Ghru

Figure 5.21: Soil profile at the source area of the sampled debris flow at the Lairig Ghru.

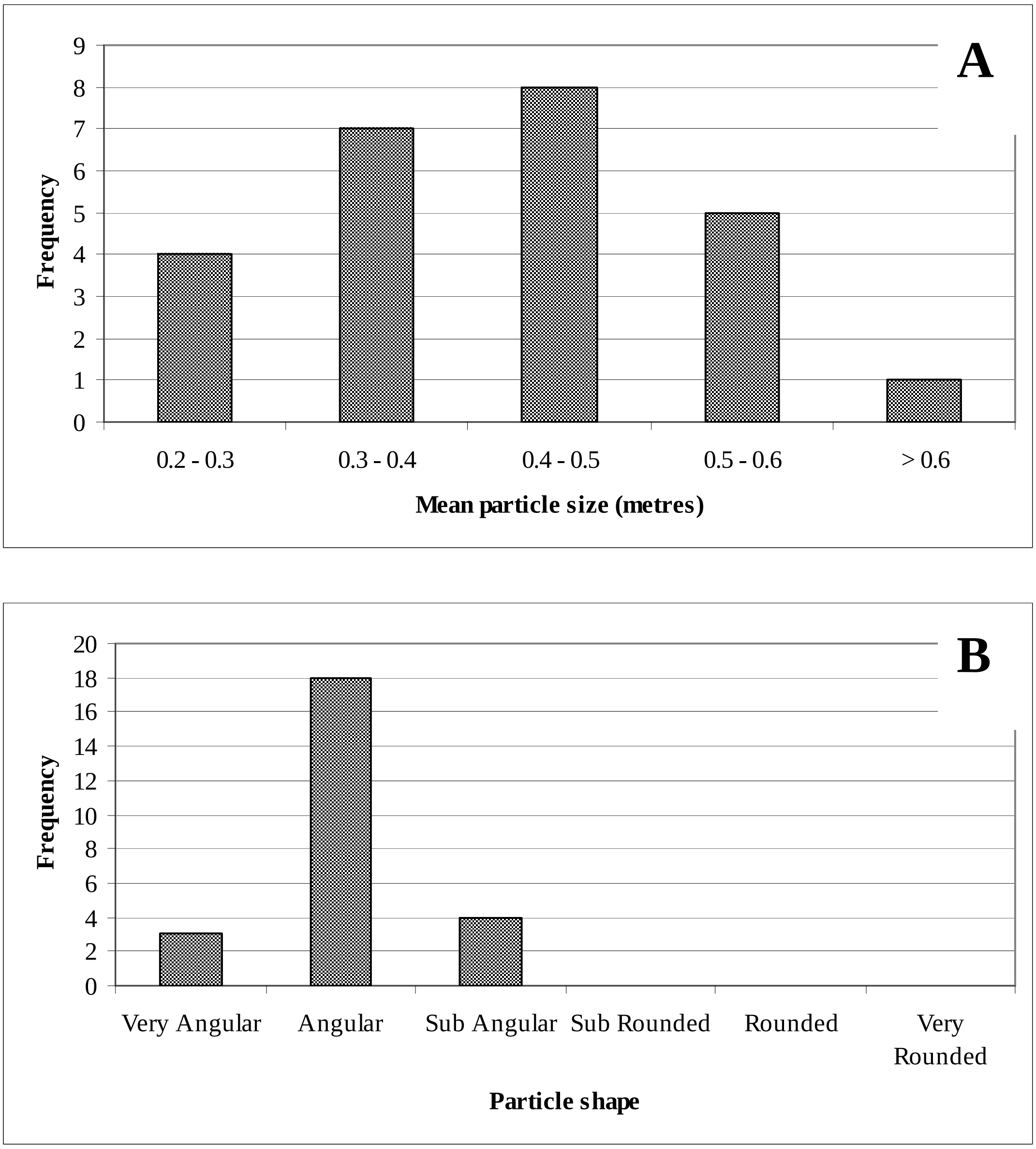


Figure 5.22: Mean particle size (a) and shape (b) frequency distribution of the largest particles in the debris deposits at the sampled Lairig Ghru debris flow.

5.2.4 Pass of Drumochter

Several examples of debris flow forms were observed on the slopes of the Pass of Drumochter (figure 5.23). Nine hillslope debris flows and a channelised debris flow exist on the slopes of Creagan Doire Dhonaich on the eastern side of the pass (figure 5.24). The channelised debris flow was initiated as a shallow translational landslide at the gully head (figure 5.25). The debris flow passes through a gully incised up to 7 m deep into the glacial drift and bedrock of the hillslope. The gully walls were in places observed to have experienced slope failure and the floor of the gully has been stripped down to the underlying bedrock by debris flow activity. The debris flow terminates at a debris cone which shows evidence of recent debris flow deposition as well as older vegetated deposits. Eight of the hillslope flows on Creagan Doire Dhonaich were initiated as shallow translational landslides on steep (*c*. 35°) open hillslopes approximately 680 mAOD. The tracks of these debris flows can be seen on the lower slopes in the shape of vegetated strips on talus reflecting deposition of finer grained material by the debris flows (figure 5.24). The source area of a further hillslope debris flow is located on a 30° slope at the edge of the summit plateau of Creagan Doire Dhonaich at 700 mAOD (figure 5.26). The source area is characterised by a landslide scar 22 m long and 58.4 m wide mantled with a veneer of weathered schist overlying the psammitic schist bedrock. The width of the landslide scar in comparison to its length suggests that the scar is the product of several smaller translational landslides. Regolith from the headscar at the source area was sampled for analysis of material properties. The soil profile was 0.47 m thick consisting of a 0.16 m thick layer of organic silty-sand overlying a 0.31 m thick layer with a greater frequency of pebble to cobble sized clasts held within a matrix consisting of the same organic silty-sand observed in the upper layer. The regolith overlies the underlying weathered psammitic schist bedrock (figure 5.27). The density of the material in the upper layer was measured as 1.08 Mg m^{-3} and for the lower layer 1.15 Mg m^{-3}. The moisture content at the time of sampling was 41.6% and 42.9% for the upper layer and lower layer respectively. After initiation in the source area the mass movement passed over approximately 10 m of steep rock crags before propagating downslope for 411 m leaving a debris track is up to 13 m wide (figure 5.28). The debris flow terminates as a debris lobe approximately 11 m long, 11.3 m across and up to 0.9 m thick on a slope with a gradient of 11°. The debris in the upper 268 m of the debris track appear to have been deposited more recently than material in the lower debris track and terminal lobe as the material in the lower part of the debris flow has been almost completely recolonised by vegetation whereas deposits in the upper reaches of the debris track have a fresher unvegetated appearance. Vegetated levees up to 0.8 m high exist just uphill of the terminal lobe and in the lower debris track. Particles with an average size up to 0.4 m were measured in the debris flow deposits with the majority of sampled clasts displaying an angular shape (figure 5.29). Debris flow deposits on Creagan Doire Dhonaich terminate approximately 100 m from the A9. Accordingly, as the magnitude of previous debris flows has been insufficient to reach the location of the road, it can be considered unlikely that future debris flow activity on this slope will represent a risk to the safe operation of the trunk road.

On the east facing slopes of the pass on the lower slopes of An Torc, several debris cones were observed (figure 5.30). These debris cones have been investigated in detail during previous research (see section 3.4; Ballantyne, 2002a, 2004b; Curry, 1998, 2000a). The debris cones have been fed from gullies cut into the thick deposits of glacial drift on the slopes of An Torc (figure 5.31). The gully walls are steep, up to *c*. 5m high and largely unvegetated. Consequently, there is a high potential for sediment recharge on to the channel floors from small scale slumping and slope wash from the gully walls (Ballantyne, 2004b). Rock outcrops on gully floors and walls were also observed to be highly weathered and subject to small scale rockfall activity leading to a lithologically driven accumulation of sediment within the gullies aggravated by the highly erodable nature of the psammitic schist bedrock. Consequently, there is an abundant supply of mobilisable material on gully floors for debris flow activity.

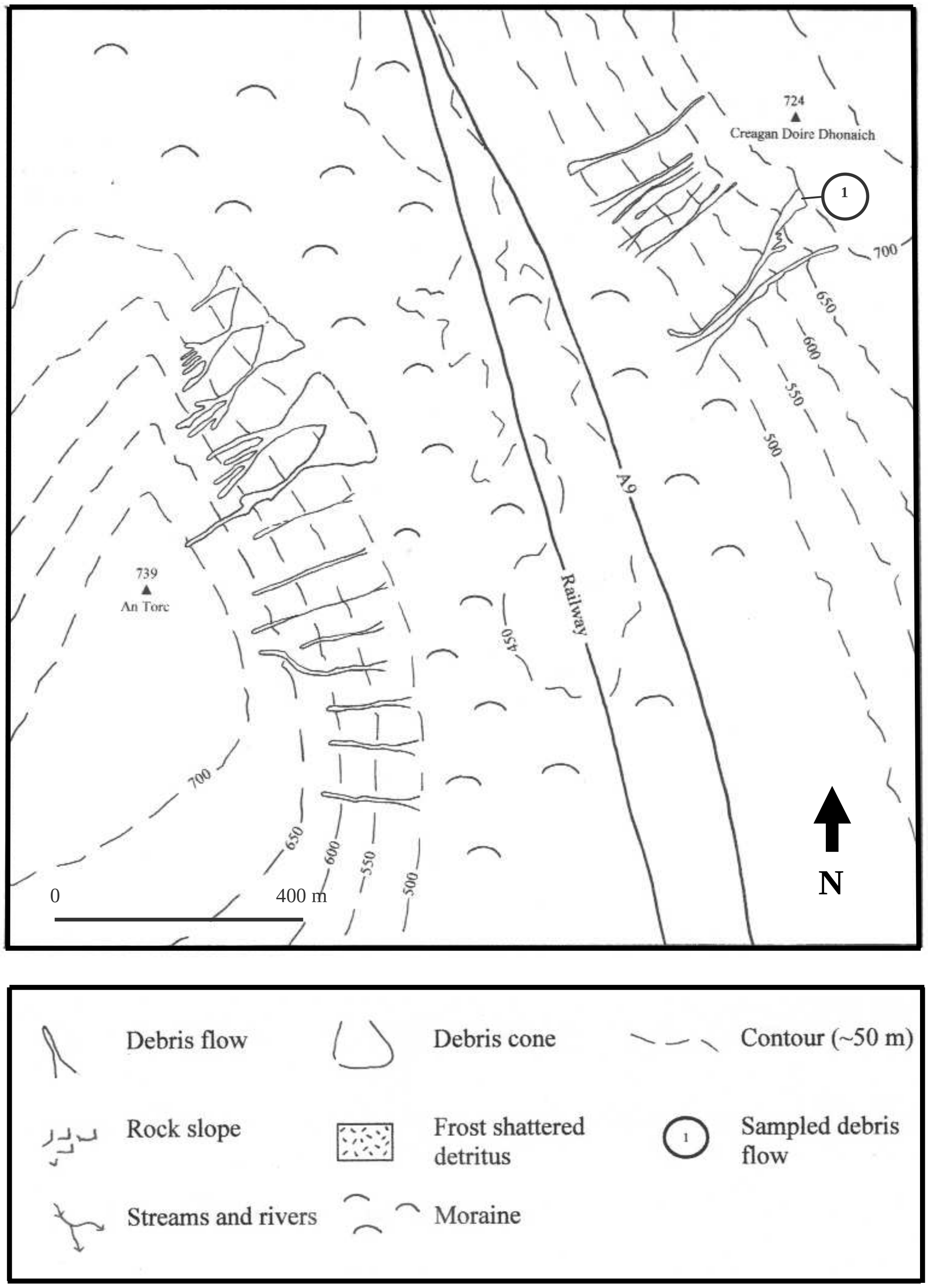


Figure 5.23: Geomorphological map of the Pass of Drumochter study site.

Figure 5.24: The west facing side of the Pass of Drumochter (Creagan Doire Dhonaich).

Figure 5.25: Source area of the channelised debris flow on Creagan Doire Dhonaich.

Figure 5.26: Source area of the sampled hillslope debris flow on Creagan Doire Dhonaich.

Figure 5.27: Soil profile at the headscar of the sampled debris flow on Creagan Doir Dhonaich.

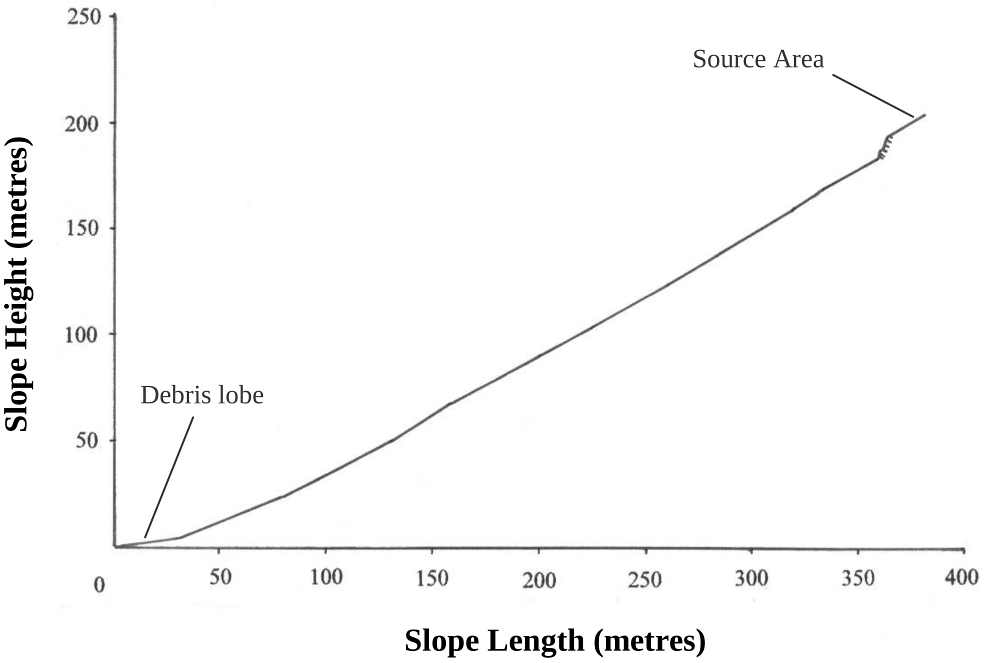


Figure 5.28: Slope profile of the sampled debris flow at the Drumochter Pass.

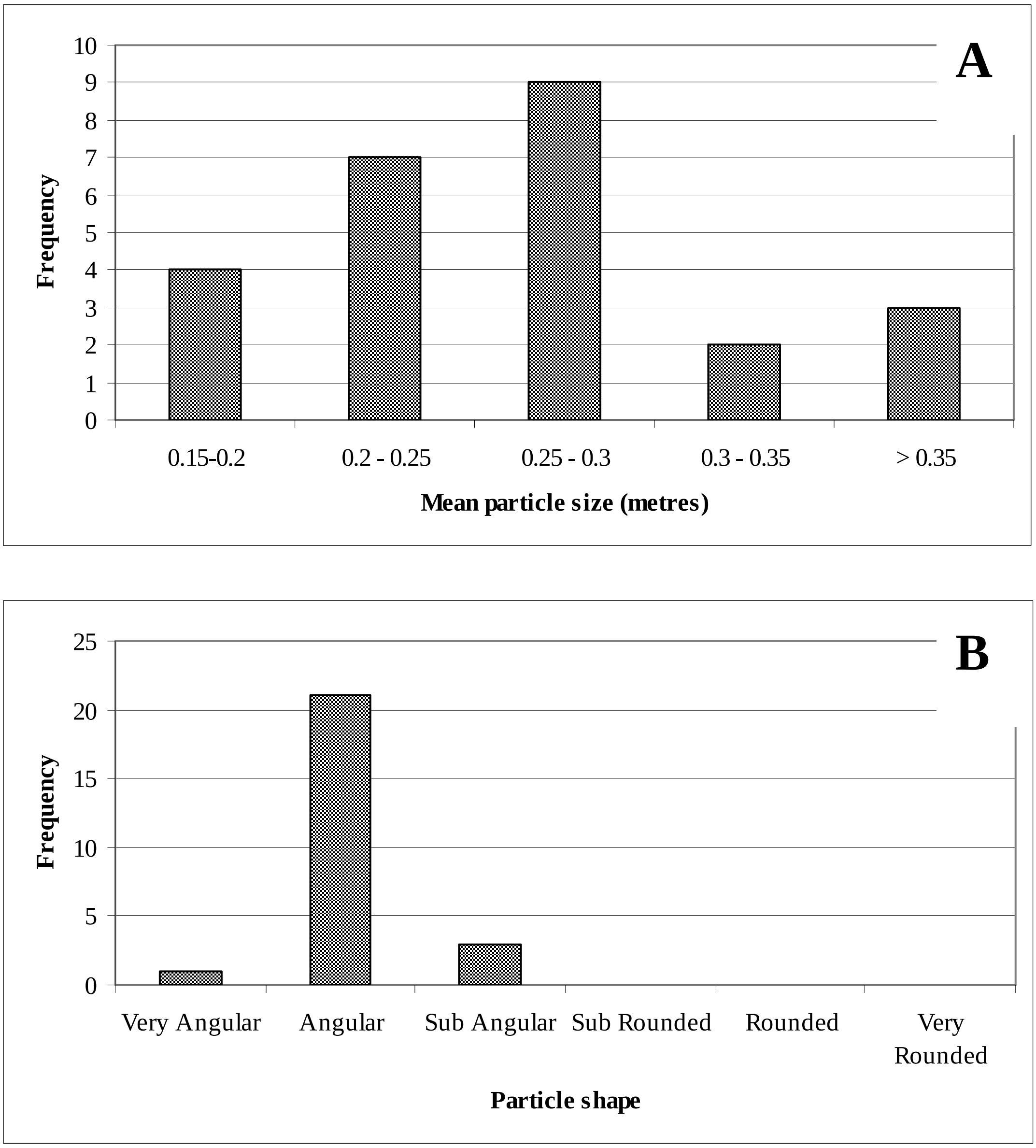


Figure 5.29: Mean particle size (a) and shape (b) frequency distribution of the largest particles in the debris deposits at the sampled Pass of Drumochter debris flow.

Figure 5.30: Debris cones on the lower slopes of the east facing side of the Pass of Drumochter (An Torc).

Figure 5.31: Exposure of glaciogenic drift in the walls of a gully feeding the largest debris cone at An Torc. The exposure is approximately 5 metres high.

5.2.5 Glen Ogle

Approximately 30 debris flows were observed in Glen Ogle all of which were generated by a high magnitude rainstorm on the 18th of August 2004 (figure 5.32). The debris flow event was characterised by the generation of both channelised and hillslope flows. Channelised debris flows mostly occurred due to the passage of hillslope flows into nearby bedrock gullies, rather than as a result of initiation within gullies from the failure of gully walls or the mobilisation of material in gully floors. Nine channelised debris flows reached the lower slopes of the glen, two of which traversed the A85 trunk road approximately 400 metres apart.

The most northerly debris flow affecting the A85 (Glen Ogle 1 – the largest debris flow to occur during the event) (figure 5.33a) was generated as a shallow translational slide close to the summit of Meall Buidhe at approximately 680 mAOD on a slope with a gradient of 21^{o}. The landslide was approximately 11 m wide and 19 m long. The source area is situated in a shallow hillslope concavity. Two small streams flow across the landslide scar (figure 5.34). On close inspection of the failure scar it was found that a thin veneer of *in situ* till and weathered schist was left mantling the bedrock. This suggests that the failure occurred in the lowest soil horizon close to the interface with the impermeable schist bedrock. Analysis of the headscar of the source landslide shows that the thickness of slope material in the source area is approximately 0.60 m. This consists of a 0.3 m horizon of well graded matrix dominated silty-sand till overlain by 0.3 m of peat (figure 5.35). The density of the peat layer at Glen Ogle 1 was found to be 1.29 Mg m^{-3} and the till layer 1.83 Mg m^{-3}. The water content at the time of sampling was 64.3% for the peat layer and 28.3% for the till layer.

Following initial failure, the sliding mass made the transition from a sliding mass movement to a flow mass movement. Evidence of this transition was apparent from the presence of islands of turf left on the landslide scar showing that the sliding mass disintegrated shortly after initiation (figure 5.34). After failure, the mass movement passed over the open hillside for approximately 60 -70 m as a hillslope debris flow leaving a slick of material over the underlying vegetation, indicative of a low viscosity and low erosivity flow. Approximately 30 m downslope of the initiating failure a second, smaller landslide scar is apparent within the track of the hillslope debris flow. This landslide was 32 m long, 6 m wide and occurred on a slope with a gradient of 22.5º. No material from the hillslope debris flow was deposited on the landslide scar indicating that this slide occurred subsequent to the shallow translational slide further upslope.

The debris flow then passed into a nearby gully, flowing downstream as a channelised flow. The Glen Ogle 1 gully is approximately 800 metres long with a mean gradient of 33° with a convex stepped profile (figure 5.36). Analysis of the debris flow sediment budget indicated that the majority of material involved in the debris flow was sourced from the gully propagation phase of the flow. The source area translational slides involved approximately 280 m^3 of material whereas approximately 8,500 m^3 of debris was deposited in the debris fan at the bottom of the slope. This material was partially entrained from the gully floor (locally eroded to the schistose bedrock by the debris flow) and partially from numerous gully wall slope failures caused by oversteepening of the slope due to erosion at the toe of the walls. Two phases of debris flow activity were apparent in the geomorphology of the gully. During the first phase the gully was filled with the flowing debris depositing a veneer of material over the gully walls. The second phase saw smaller volumes of material passing down the gully leading to erosion and trenching of the stream bed (figure 5.37).

The debris flow came to rest on a slope of approximately 8°, passing over an 18th century military road and finally flowing into the Ogle Burn on the floor of the glen (figure 5.38). During the storm event the Ogle Burn was in spate and debris deposited on the floor of the glen were evacuated by a flood estimated to have peaked at *c*. 120 m^3s^{-1} with velocities of *c*. 3 ms^{-1} (Black *et al*. 2005). The debris flow fan was characterised by a thin sheet like morphology with no levee development. This is indicative of a relatively fluid debris flow rheology. Anecdotal evidence of only minor damage to the A85 road surface despite the presence of large boulders in the flow also suggests that the mass movement was buoyant in nature. The debris flow deposits comprised well graded, silty-sand material including large boulders with mean sizes of up to 3 m and trees (figure 5.39; figure 5.40).

Inspection of exposed sections in the debris fan revealed evidence of previous debris flow activity at the site in the form of buried debris flow deposits and organic horizons beneath the August 2004 deposits. These are shown in figure 5.41 with distinct colluvial deposits from successive debris flows demarked by dashed lines and numbered 1 to 4 from the youngest (18th of August 2004) to the oldest. Older debris flow deposits may also be buried below deposit 4. The age of these palaeo-deposits has yet to be determined. The geomorphology surrounding the Glen Ogle 1 debris flow takes the form of uneven ground and boulder deposits similar in nature to the 2004 debris flow deposits. Angular clasts overlying the old road surface within 100 m of where the 2004 debris flow crossed the military road to the Ogle Burn, provide further evidence of previous debris flow activity.

The Glen Ogle 2 debris flow was significantly smaller in magnitude than Glen Ogle 1 and originated as a shallow translational landslide on a convex slope at approximately 500 mAOD (figure 5.32; figure 5.33b). The initiating landslide was approximately 14 m wide and 34 m long, involved approximately 285 m^3 of material and occurred on a gradient of 22°. The regolith profile at the headscar is characterised by a 0.21 m layer of till overlain by a 0.38 m of peat. The failure plane corresponds with the interface between the till layer and the mica-schist bedrock, the failure scar existing as exposed weathered bedrock. The configuration of drainage channels in peat deposits upslope of the source area indicates a convergence of overland flow at this location on the hillslope (figure 5.42) resulting in preferential saturation of the slope material and reduced slope stability. The initiating slide made the transition to a hillslope flow mass movement before entering a bedrock gully, incising the stream channel and propagating to the bottom of the glen, blocking the A85 *en route*. The Glen Ogle 2 gully is 610 metres long and has a mean gradient of 25° (figure 5.36). The deposition fan was characterised by 3 separate lobes consisting of sub-rounded to angular particles with mean sizes of up to 0.51 metres (figure 5.43; figure 5.44). The volume of material deposited in the Glen Ogle 2 debris lobes was calculated to be approximately 3200 m^3.

To the south of Glen Ogle 2 a group of hillslope and channelised debris flows termed the Glen Ogle 3 group were initiated. At this location on the hillslope a farm track runs up the side of the slope. Several debris flows impacted upon this track causing damage to culverts and destroying the track at locations where channelised debris flows passed along the stream beds. The track also acted as a catchwater causing debris flows to pass along the side of the track eroding a deep trench. This had the effect of redirecting the route of debris flows and concentrating the flow in gullies further along the track. Channelised debris flows at this location reached the bottom of the slope and were comparable in size to the Glen Ogle 2 debris flow. These flows did not affect the A85 as at this location the road is situated away from the slope foot. The debris flows were triggered where there is an extensive coverage of hill peat. However, since all the flows were initiated in the mineral soil layer, they can be classified as debris flows rather than peat slides or peat flows.

On the west side of the glen at least 12 debris flows were triggered. These were not studied in great detail in the field. There was no significant difference in the number of debris flows triggered on each side of the glen.

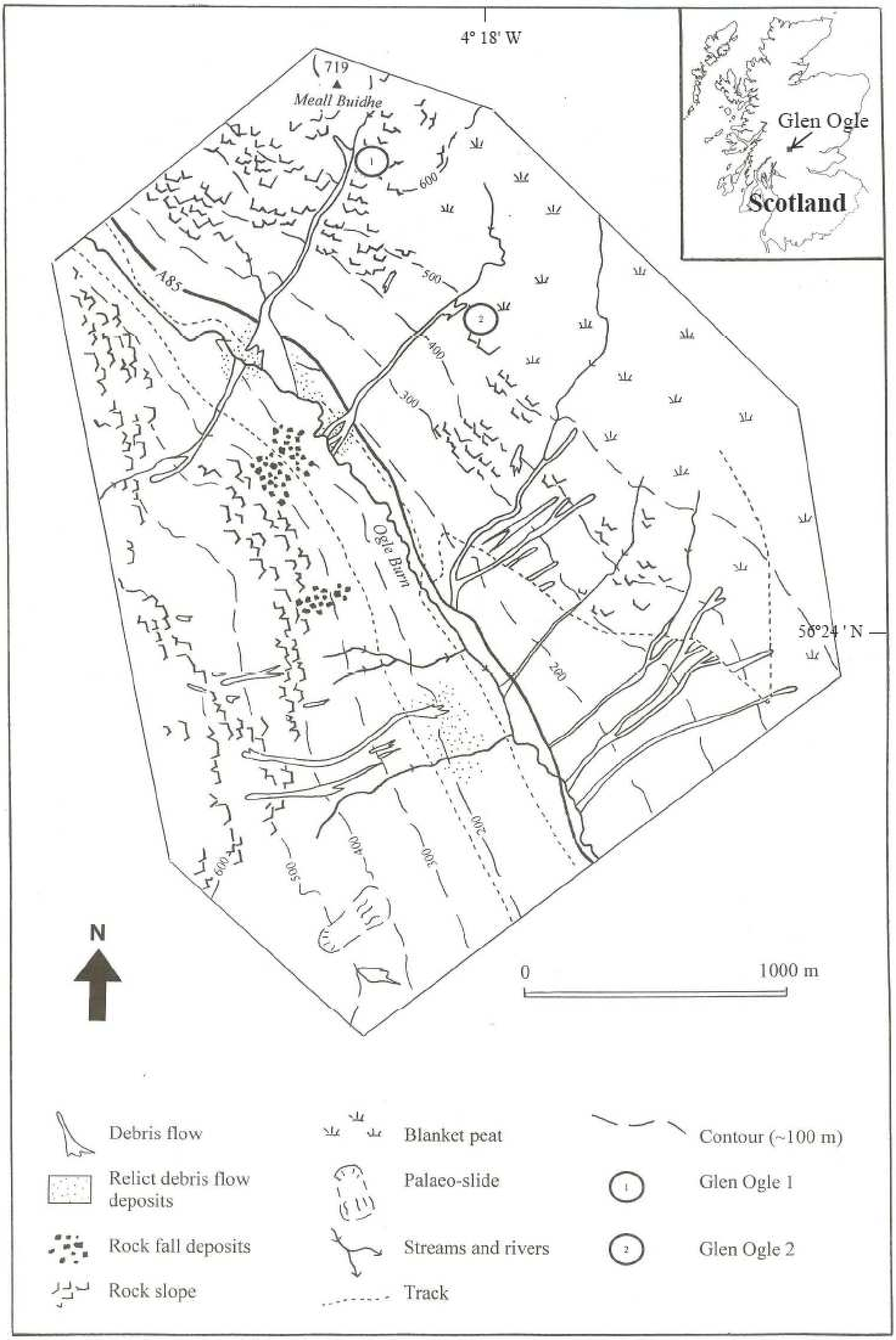


Figure 5.32: Geomorphological and location map of Glen Ogle showing debris flows generated on the 18th of August 2004.

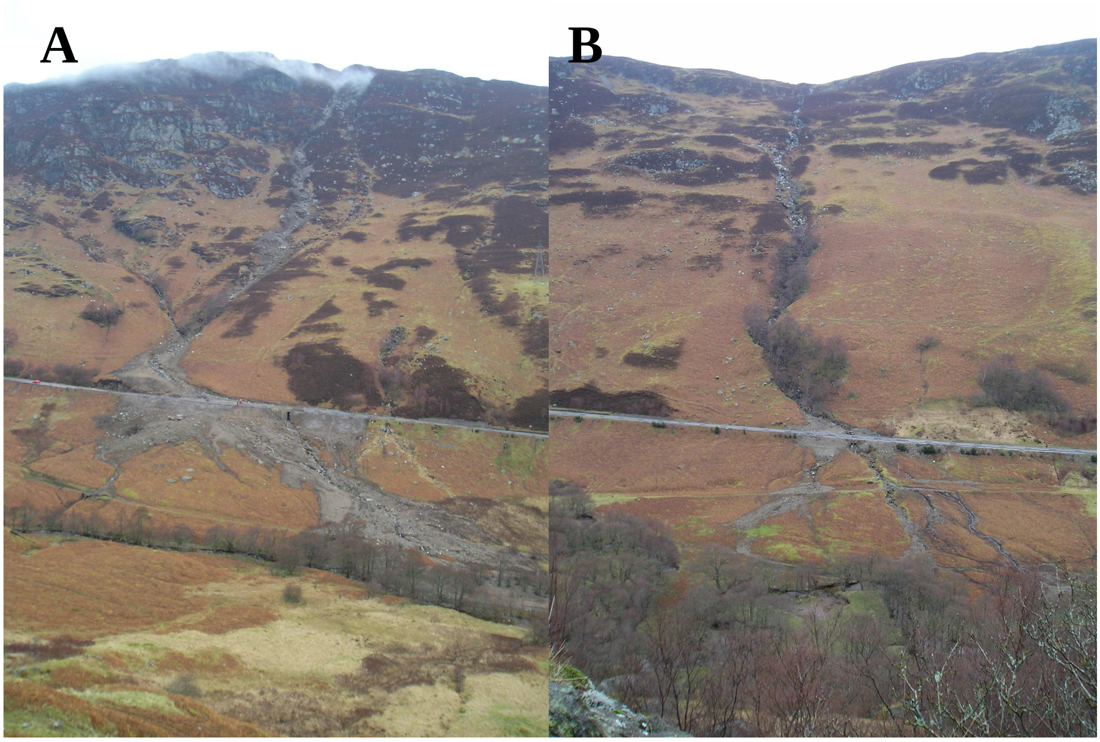


Figure 5.33: Glen Ogle 1 (A) and Glen Ogle 2 (B) debris flows.

Figure 5.34: Glen Ogle 1 debris flow initiating landslide. The source area exists in a shallow hillslope depression with two small streams running over the area of the landslide scar.

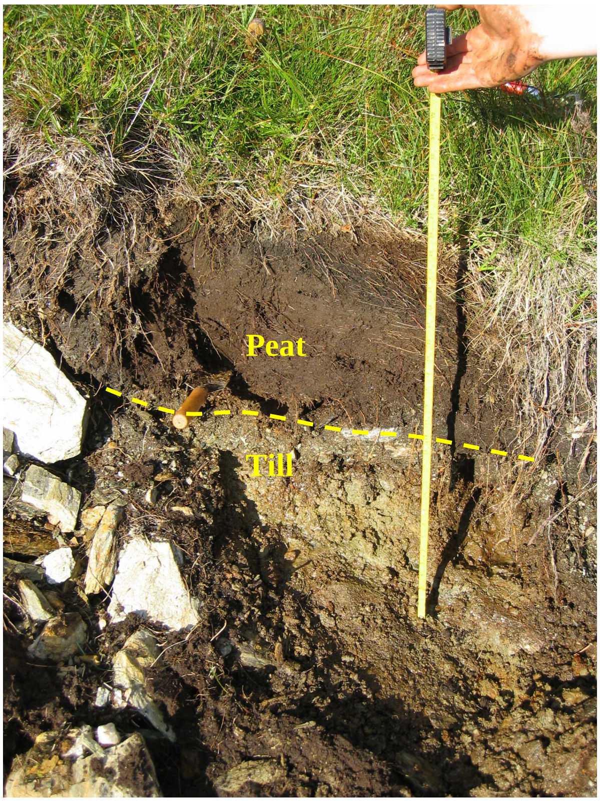


Figure 5.35: Exposed profile at headscar of Glen Ogle 1 source landslide.

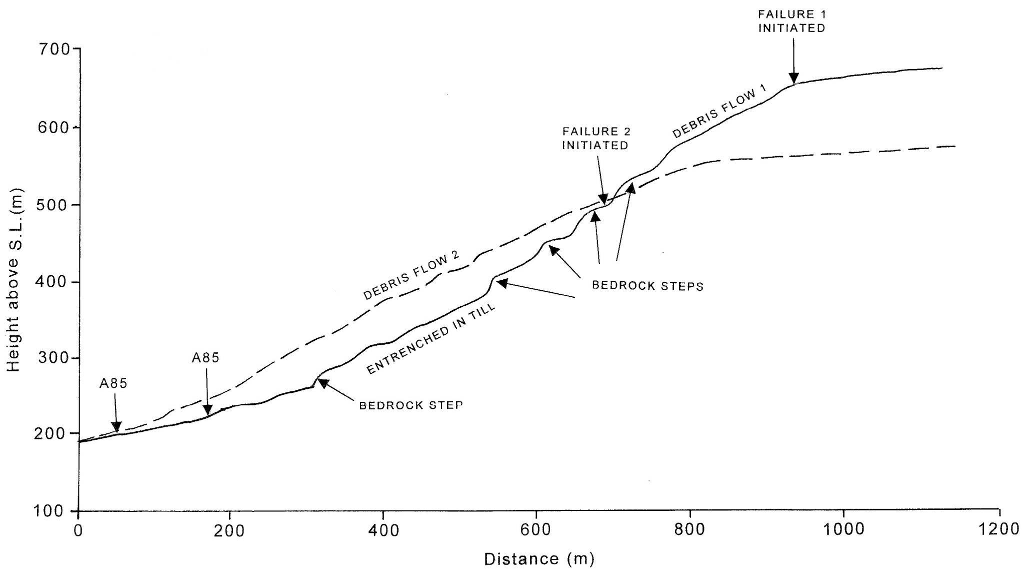


Figure 5.36: Long profiles of the Glen Ogle 1 (solid line) and Glen Ogle 2 (dashed line) debris flows (Milne *et al*. *in press*).

Figure 5.37: Glen Ogle 1 lower showing variation in deposited material types which indicates a two-phase debris flow event (Milne *et al. in press*).

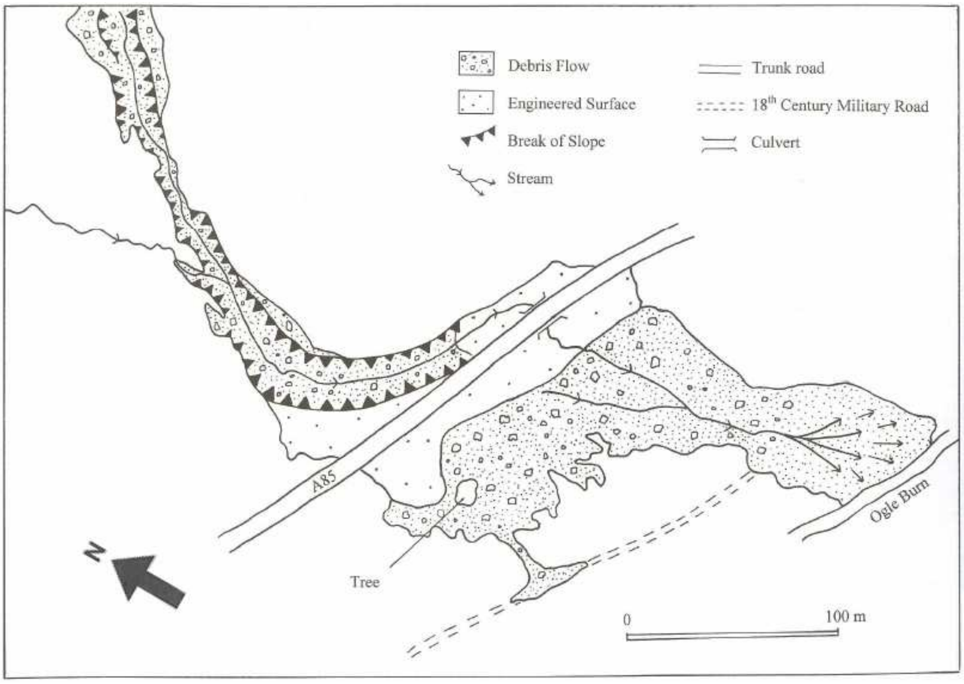


Figure 5.38: Plan of the Glen Ogle 1 debris flow fan (Milne *et al. in press*).

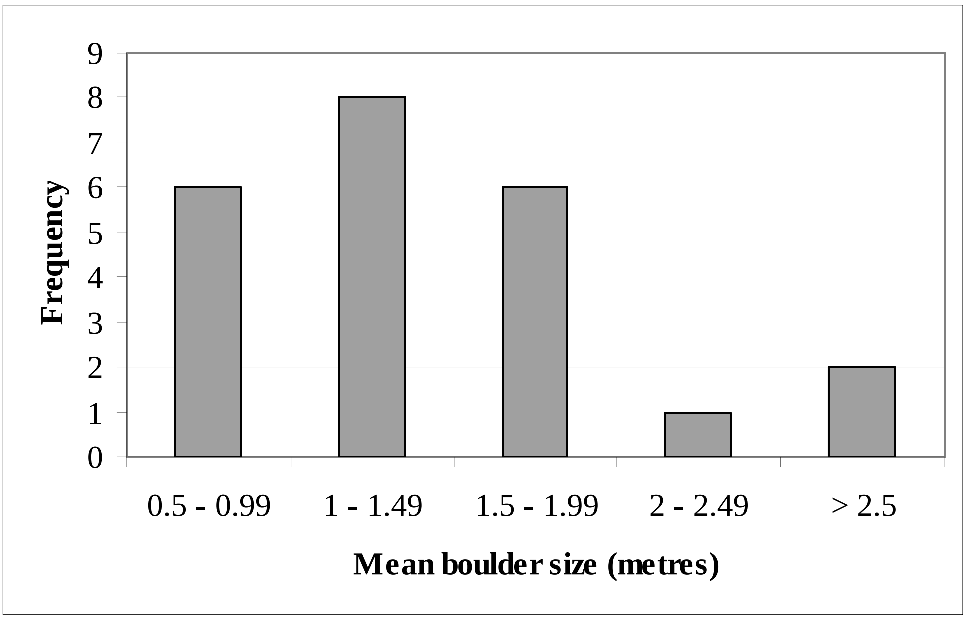


Figure 5.39: Mean boulder size frequency distribution of the largest particles on the Glen Ogle 1 debris fan.

Figure 5.40: Large boulders deposited in the debris fan below the A85.

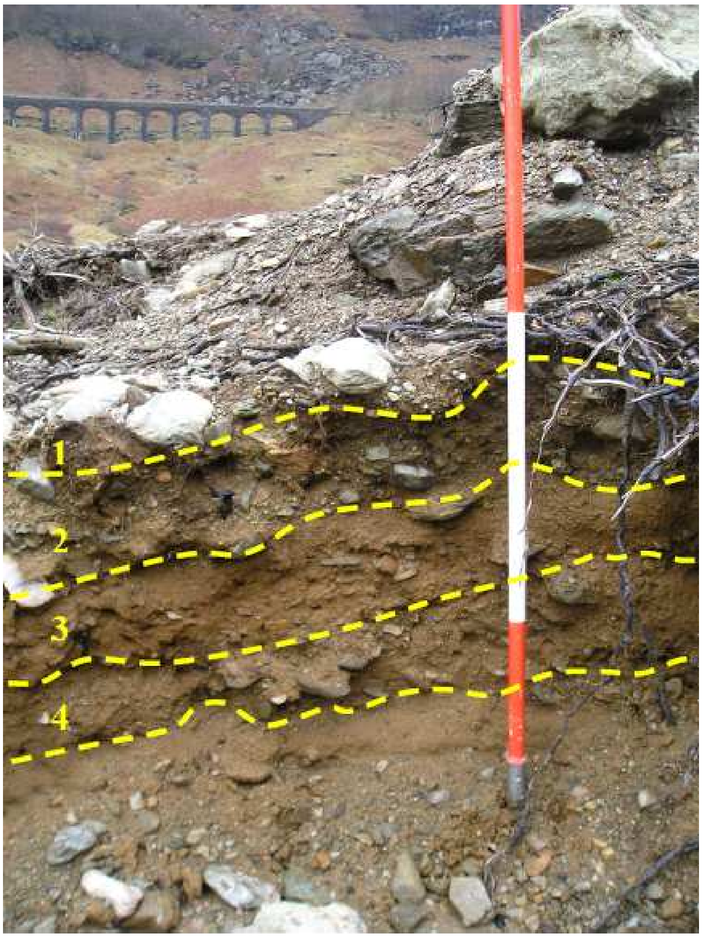


Figure 5.41: Stratigraphic evidence of previous debris flow activity at Glen Ogle 1 in the form of buried palaeosols beneath the 2004 deposits.

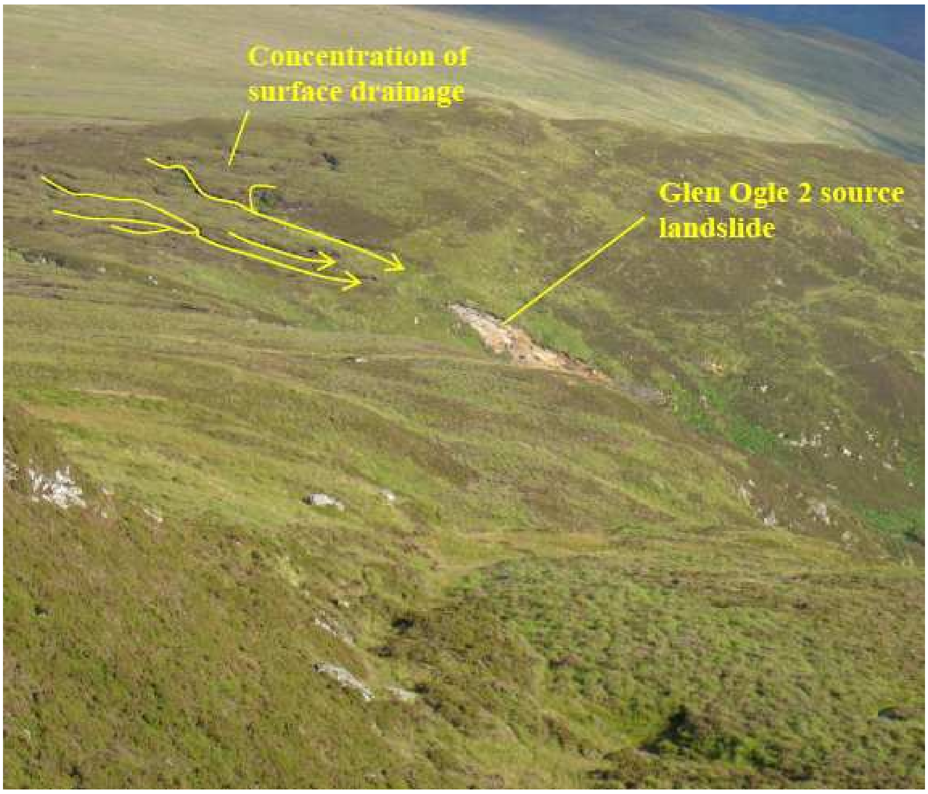


Figure 5.42: Source area of the Glen Ogle 2 source landslide showing the convergence of overland flow demarked by drainage channel configuration in upslope peat deposits.

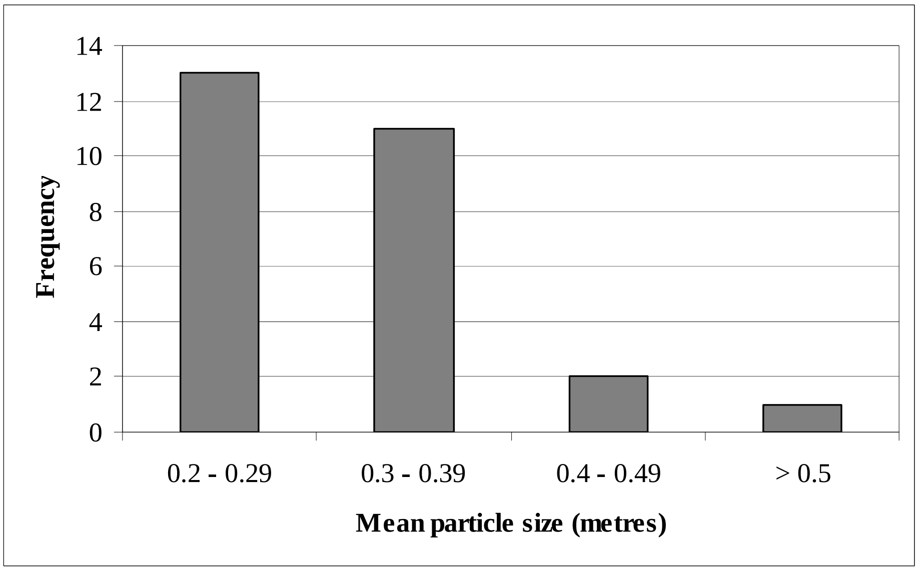


Figure 5.43: Mean particle size frequency distribution of the largest particles on the Glen Ogle 2 debris fan.

Figure 5.44: Debris deposited in the Glen Ogle 2 fan below the A85.

5.2.6 Mill Glen

The Mill Glen study site follows the course of the Gannel Burn, through a v-shaped valley in the upper reaches of the glen. Debris flow activity at the study site was characterised by the presence of 6 small debris flows approximately 10 - 70 m in length situated on the north facing side of the glen (figure 5.45). The steeper lower slopes of the glen are highly abundant in shallow drift-cut gullies (figure 5.46). The formation of such gullies occurs when the frictional resistance of the slope material is exceeded by the erosive power of surface runoff (Harvey, 1992). The walls and floors of the gullies are vegetated indicating that they have not experienced recent large scale erosion and are thus relict features.

The debris flows evident at the study site are all generated from shallow translational landslides with 5 of the debris flows following the course of relict gullies. Gully propagation of the debris flows appeared to be passive as there was no evidence of erosion of the channel floor caused by the observed debris flows. One of the debris flows at the site was sampled for further analysis (figure 5.45; figure 5.47). The debris flow was initiated as a shallow translational landslide on a slope with a gradient of 31º leaving a landslide scar 4.9 m across and 9.2 m long. The exposed profile at the landslide headscar was found to consist of a 0.26 m thick layer of well graded organic silty-sand brown forest soil overlying a well graded 0.18 m thick layer of soliflucted till characterised by angular gravel to cobble sized clasts in a red-brown silty-sand matrix (figure 5.48). The failure plane corresponds with the bottom of the exposed headscar profile at a depth of 0.44 m. It was difficult to excavate below the failure plane although the slope material below the failure plane appears to consist of the same material as the overlying horizon. The upper layer of brown forest soil was found to have a density of 1.72 Mg m^{-3} and the matrix of the soliflucted till layer 1.67 Mg m^{-3}. The sample moisture content was 26.5% for the brown forest soil and 39.4% for the soliflucted till layer. Following the initiating failure the debris flow passed downslope for 72.8 m within the confines of a shallow relict drift cut gully up to 1.7 m deep and 7 m wide (figure 5.49). Debris from the flow does not terminate as a debris fan or lobe, instead gradually dissipating downslope (figure 5.47). This indicates that only a small volume of material, insufficient to reach the toe of the slope was involved in the debris flow. There is no evidence of accumulation of material during debris flow propagation from erosion of the gully walls or floor. It can therefore be ascertained that the volume of material comprised in the debris flow is equal to the volume of the initiating translational failure (*c*. 20 m^3). The debris deposits are characterised by the presence of gravel to cobble sized sub angular to very angular particles (figure 5.50).

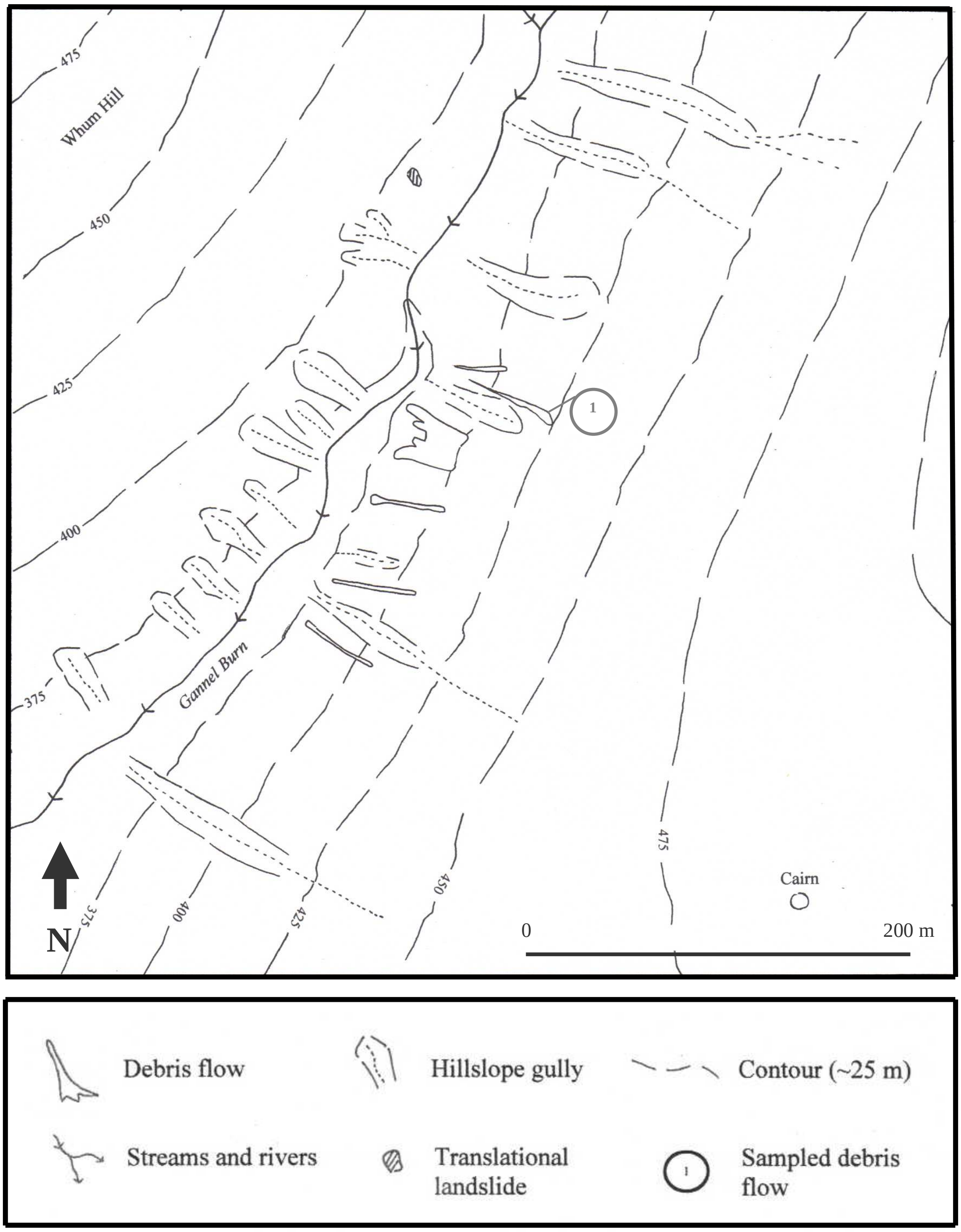


Figure 5.45: Geomorphological map of Mill Glen study site.

Figure 5.46: Relict drift cut gullies on steeper lower slopes of Mill Glen.

Figure 5.47: Sampled debris flow at Mill Glen study site.

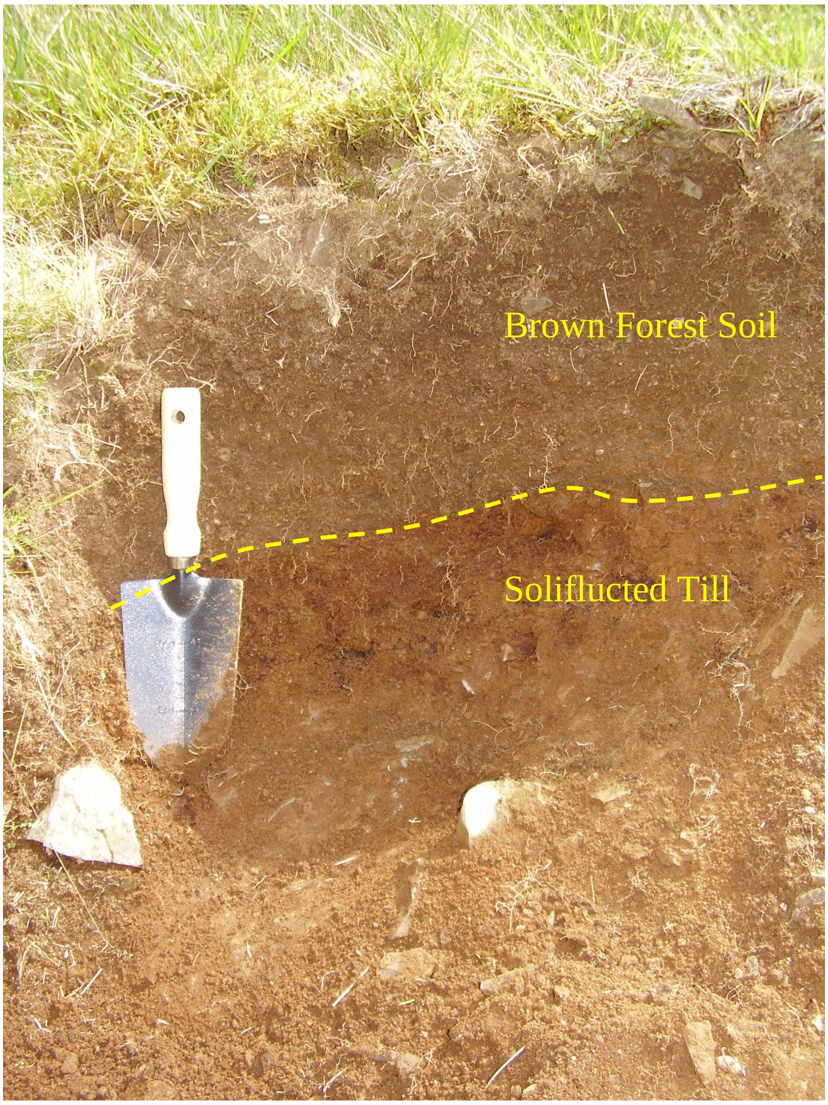


Figure 5.48: Exposed profile at headscar of source landslide.

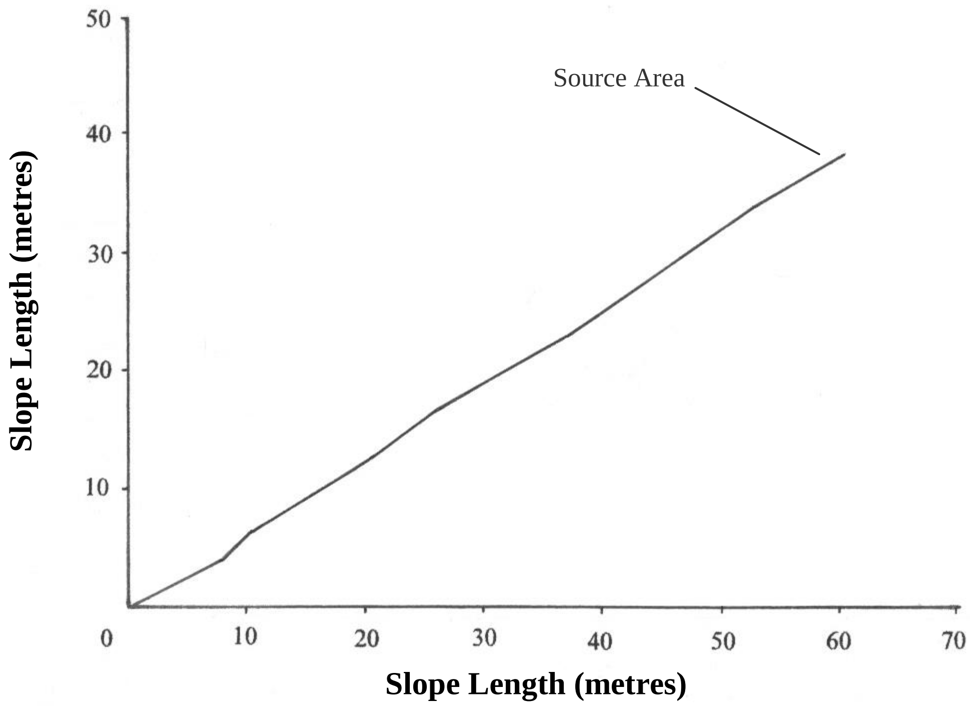


Figure 5.49: Slope profile of sampled debris flow at Mill Glen.

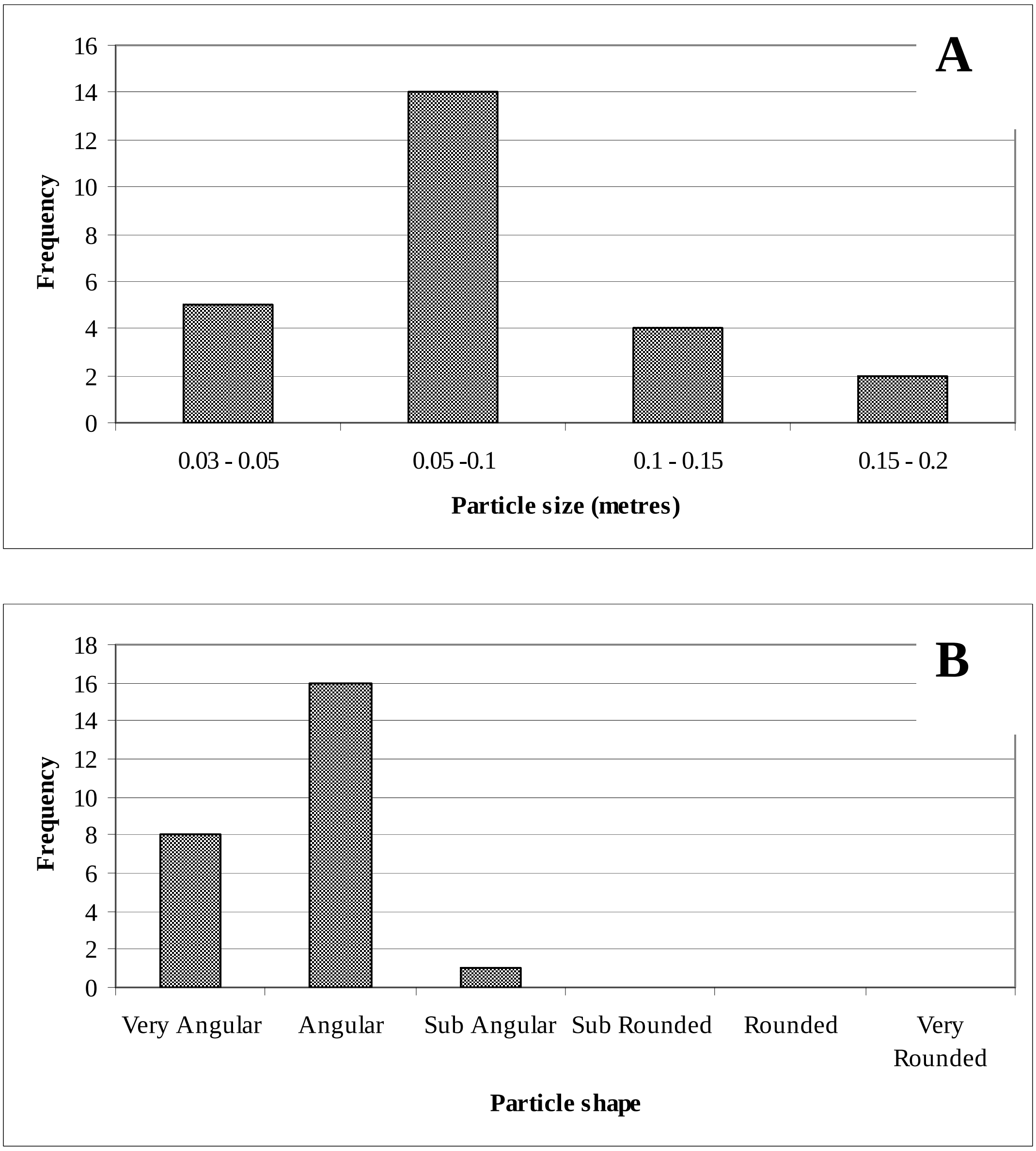


Figure 5.50: Mean particle size (a) and shape (b) frequency distribution of the largest particles in the debris deposits at the sampled Mill Glen debris flow.

5.3 Summary

The measured debris flow densities show a pattern in which study sites which are underlain by coarse grained granite and sandstone lithologies display higher spatial densities of debris flows compared to those with finer grained lithologies which tend to have a lower frequency of debris flow.

9 debris flows were measured in the field to allow closer analysis of the topographic and material controls on the debris flow process. Measurements related to the geometric properties of these debris flows and material properties sampled at source areas are summarised in table 5.3 and table 5.4 respectively. The range in soil depths down to the failure plane was found to be between 0.29 m and 0.63 m for the Glamaig (basalt) and the An Teallach 2 debris flows. The *in situ* dry density of sampled soils in horizons corresponding closely with the failure plane range between 0.63 Mg m^{-3} for the organic silty sand at Drumochter and 1.54 Mg m^{-3} for the aeolian sand sampled at the source area of An Teallach 1. Of the sampled debris flows there are six hillslope debris flows and three channelised debris flows. More generally, the majority of debris flows observed in the field were of the hillslope variety. The debris flows range in length between 73 m (Mill Glen) and 800 m (Glen Ogle 1) long. The source areas gradients fall into a range of 21° (Glen Ogle 1) to 36.5° (An Teallach 2). Sampled source volumes range from 13m^3 (An Teallach 1) to *c*. 604 m^3 (Drumochter Pass) whereas measured fan/lobe volumes range from >20m^3 (Mill Glen) to *c*. 8500 m^3 (Glen Ogle 1).

Sampled debris flow deposit dimensions are summarised in table 5.5. The average mean particle size of sampled debris flow deposits range between 0.09 m

(Mill Glen) and 1.45 m (Glen Ogle 1). The majority of sampled deposits were sub-angular to very angular in shape.

Debris Flow	**Flow type**	**Total Debris Flow Length** (m)	**Source** (°)	**Propagation** (°)	**Deposition** (°)	**Source Volume** (m^3)	**Approximate Terminal Fan/Lobe Volume** (m^3)
An Teallach 1	Hillslope	103	36	30.7	21	13	59
An Teallach 2	Channelised	135	36.5	33.5	20	63	90
Glamaig (basalt)	Hillslope	158	31	28	20.5	181	183
Glamaig (granite)	Hillslope	231	35.5	33	27.5	546	731
Lairig Ghru	Hillslope	385	35.5	30	11	306	1530
Drumochter	Hillslope	435	30	29.5	11	604	391
Glen Ogle 1	Channelised	800	21	33	8	280	8500
Glen Ogle 2	Channelised	610	22	25	12	285	3200
Mill Glen	Hillslope	73	31	34.6	28.5	20	> 20

Table 5.3: Summary of geometric properties of sampled debris flows.

Debris Flow	**Headscar soil profile** (m)		**Density** (Mg m^{-3})	**Moisture Content** (%)	**Dry Density** (Mg m^{-3})
An Teallach 1		0.3	1.7	9.4	1.54
An Teallach 2		0.63	1.53	6.3	1.43
Glamaig (basalt)		0.29	1.15	34.4	0.76
Glamaig (granite)		0.31	1.57	36.9	0.99
Lairig Ghru		0.42	1.06	14.1	0.91
Pass of Drumochter	*B horizon*	0.16	1.08	41.6	0.63
	C horizon	0.31	1.15	42.9	0.66
		0.47			
Glen Ogle 1	*Peat*	0.3	1.29	64.3	0.46
	Till	0.3	1.83	28.3	1.31
		0.6			
Glen Ogle 2	*Peat*	0.38	1.18	75.1	0.29
	Till	0.21	1.61	51.4	0.78
		0.59			
Mill Glen	*Forest soil*	0.26	1.72	26.5	1.27
	Soliflucted till	0.18	1.67	39.4	1.01
		0.44			

Table 5.4: Summary of soil profiles and densities of sampled debris flow headscars.

Debris Flow	**Range in mean size of largest particles in debris flow deposits** (metres)	**Average mean particle size in debris flow deposits** (metres)	**Range of debris flow deposit particle shape**
An Teallach 1	0.21 - 0.85	0.41	Sub Angular - Angular
An Teallach 2	0.22 - 0.61	0.34	Sub Angular - Angular
Glamaig (basalt)	0.09 - 0.37	0.18	Angular - Very Angular
Glamaig (granite)	0.17 - 0.48	0.28	Sub Angular - Very Angular
Lairig Ghru	0.24 - 0.71	0.42	Sub Angular - Very Angular
Drumochter	0.17 - 0.40	0.26	Sub Angular - Very Angular
Glen Ogle 1	0.83 - 2.59	1.45	Sub Rounded - Angular
Glen Ogle 2	0.20 - 0.51	0.31	Sub Rounded - Angular
Mill Glen	0.03 - 0.20	0.09	Sub Angular - Very Angular

Table 5.5: Summary of sampled debris flow deposit dimensions.

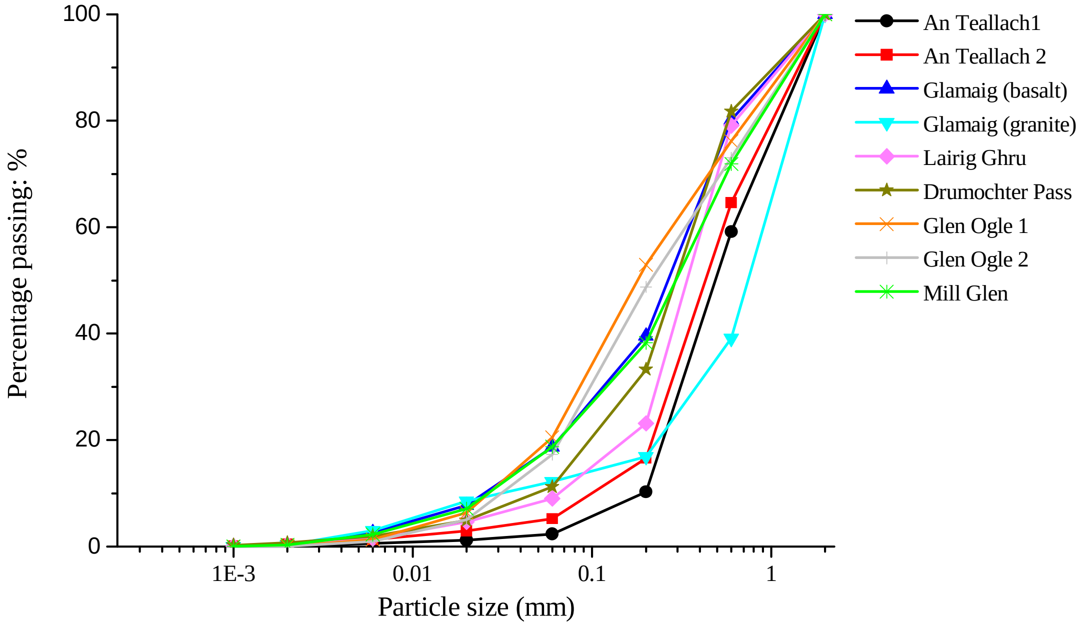
6. Material Properties

Sampled soil from the source areas of debris flows were investigated to determine the key material properties that can influence the susceptibility of a hillslope to debris flow. The results of investigations into the particle size distribution, particle shape, organic content, permeability and effective strength parameters of sampled soil matrixes are presented in this chapter.

6.1 Particle Size Distribution

Particle size analysis showed that all of the sampled soil matrixes were found to be dominated by sand sized particles with each regolith comprising upwards of 79.5% sand (figure 6.1; figure 6.2; table 6.1). The debris flow source areas sampled at An Teallach and the Lairig Ghru were found to have the sandiest sediment textures, consisting of over 90% sand sized particles. Regolith sampled at the An Teallach 1 and An Teallach 2 debris flows was found to have sand fractions of 97.6% and 94.8% respectively whilst at the Lairig Ghru sand sized particles comprised 91% of the soil matrix. The source areas sampled at Glen Ogle, on the basaltic part of Glamaig and at Mill Glen were found to have the finest regolith textures with 20.4% and 17.2% silt fractions for Glen Ogle 1 and Glen Ogle 2 respectively, 18.4% for Glamaig and 18.5% at Mill Glen. The silt fraction of the regolith from the granitic part of Glamaig (11.8%) is slightly higher than the silt component of soil developed over granite bedrock at the Lairig Ghru study site (8.7%). The soil sampled at the Pass of Drumochter was found to have a sandier matrix than other sampled soils derived from fine grained lithologies. The clay fraction (< 0.002 mm diameter particles) of the sampled regoliths was very low. The Pass of Drumochter sample had the highest proportion of clay sized particles at 0.7%, whilst all the other sampled soils registered less than 0.5%. The lowest proportions of clay were recorded at the Glen Ogle study site with 0.1% and 0.04% clay fractions measured at Glen Ogle 1 and Glen Ogle 2 respectively.

The sand fraction is dominated by medium sized sand particles for all of the regoliths except for those sampled at Glen Ogle and at the granitic part of Glamaig (figure 6.2). The regolith sampled from the granite part of Glamaig is dominated by coarse sand, with particles of that size comprising 60.9% of the soil matrix. At Glen Ogle the sand fraction is dominated by fine sand at both Glen Ogle 1 (32.4% of the soil matrix) and Glen Ogle 2 (31.5% of the soil matrix). The silt fraction for all the sampled regoliths except Glamiag (granite) is dominated by coarse silt. In the Glamaig (granite) regolith medium silt dominates the silt fraction (figure 6.2). Based upon the classification of soils from BS 5930 (1981) (table 4.1) the sampled regoliths matrixes from An Teallach can be considered as *slightly silty sands*, the matrixes from Glamaig (granite), the Lairig Ghru and the Pass of Drumochter are *silty sands* and the regoliths from Glen Ogle, Mill Glen and the basalt part of the Glamaig study site are classified as *very silty sands*. This suggests a lithologically forced determination on soil type with sandstone yielding slightly silty sands, Granites and psammitic schists generating silty sands and very silty sands developing over mica schists and extrusive igneous lithologies (table 6.1).



Clay	fine	medium	coarse	fine	medium	coarse
	Silt			Sand		

Figure 6.1: Particle size distribution curves for sampled regolith matrixes at debris flow source areas.

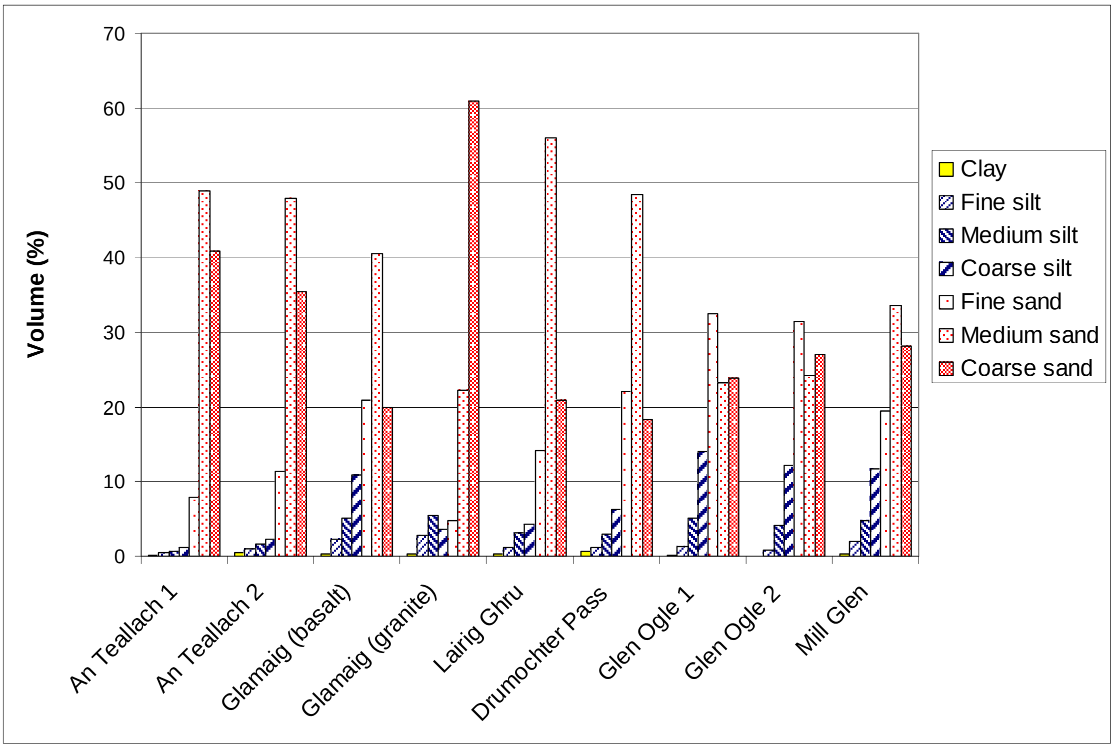


Figure 6.2: Bar chart showing distribution of particle size types in the sampled regolith matrixes.

Sample	Lithology	% clay (<0.002 mm)	% Silt (0.002 -0.06 mm)	% Sand (0.06 - 2 mm)	Soil Group (BSI, 1981)
An Teallach 1	Sandstone	0.2	2.2	97.6	Slightly silty SAND
An Teallach 2	Sandstone	0.4	4.8	94.8	Slightly silty SAND
Glamaig (basalt)	Basalt	0.3	18.4	81.3	Very silty SAND
Glamaig (granite)	Granite	0.3	11.8	87.8	Silty SAND
Lairig Ghru	Granite	0.3	8.7	91.0	Silty SAND
Drumochter Pass	Psammitic schist	0.7	10.5	88.8	Silty SAND
Glen Ogle 1	Mica schist	0.1	20.4	79.5	Very silty SAND
Glen Ogle 2	Mica schist	0.0	17.2	82.7	Very silty SAND
Mill Glen	Andesite	0.3	18.5	81.2	Very silty SAND

Table 6.1: Lithology, matrix percentage composition of clay, silt and sand particles, and soil group for each sampled regolith.

6.2 Particle Shape

A range of particle shapes were observed in the sampled soil matrixes (table 6.2). All the matrixes consist of particles which display angularity. The most angular sample is Glamaig (granite), with a range of very angular to angular particles. Mill Glen also comprises of very angular particles but is also characterised by angular and sub-angular particles. The most rounded particles were observed in the soil matrixes from An Teallach which comprise sub-angular to sub-rounded particles.

Both elongate and spherical particles were observed in the matrixes of the Glamaig (granite), Glamaig (basalt) and Lairig Ghru regoliths. At An Teallach particles are spherical in shape whilst both tabular and elongate particles were observed in the soil matrix in samples from Glen Ogle. The samples from Mill Glen and the Pass of Drumochter are characterised by a mixture of shapes with spherical, tabular and elongate particles observed in the samples.

Sample	**Angularity**	**Particle shape**
An Teallach 1	sub-angular to sub-rounded	spherical
An Teallach 2	sub-angular to sub-rounded	spherical
Glamaig (granite)	very angular to angular	elongate; spherical
Glamaig (basalt)	angular to sub-angular	elongate; spherical
Lairig Ghru	angular to sub-angular	elongate; spherical
Drumochter Pass	angular to sub-angular	spherical; tabular; elongate
Glen Ogle 1	angular to sub-rounded	tabular; elongate
Glen Ogle 2	angular to sub-rounded	tabular; elongate
Mill Glen	very angular to sub-angular	spherical; tabular; elongate

Table 6.2: Particle shape and angularity of the sampled regolith matrixes.

6.3 Organic Content

Loss on ignition tests on the organic matter showed that sampled regolith from the basalt part of Glamaig had the highest organic content at 25.1% weight of the dry mass of soil (figure 6.3). Comparatively high organic contents were also found in samples from Glen Ogle 2 (23.8%), the Drumochter Pass (23.6%) and the granitic slopes of Glamaig (21.7%). The lowest organic contents were measured at An Teallach 1 (1%), An Teallach 2 (1.2%) and Glen Ogle 1 (1.7%). The regolith at Mill Glen was found to have an organic content of 14% and at the Lairig Ghru the organic content is 6.1%. Based upon the classification of organic soils as outlined in BS 5930 (1999) (table 4.2), the Lairig Ghru and Mill Glen samples are considered as having a "medium organic content" and are classified as *organic soils* whereas the samples from Glamaig, the Drumochter Pass and Glen Ogle 2 have a "high organic content" and are considered *very organic soils*. As the organic contents of An Teallach 1, An Teallach 2 and Glen Ogle 1 are lower than 2%, they are not regarded as organic soils (BSI, 1999) (table 6.3).

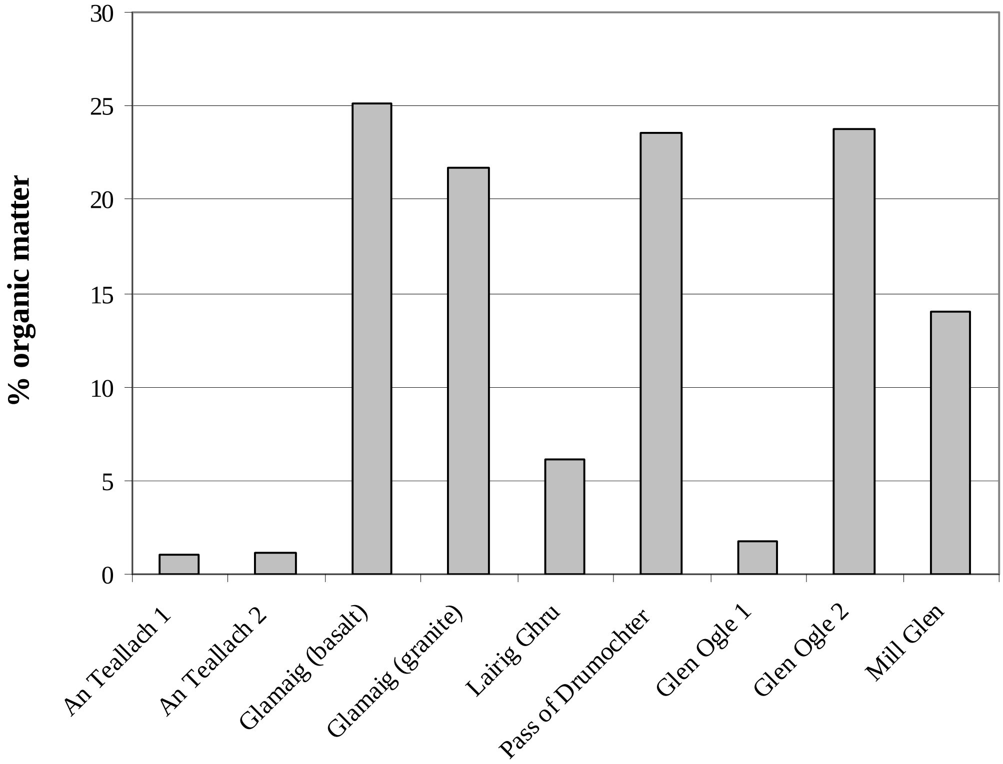


Figure 6.3: Percentage organic matter for each sampled regolith.

Sample	**Organic content** (% weight of dry mass)	**Term** (BSI, 1999)
An Teallach 1	1.0	-
An Teallach 2	1.2	-
Glamaig (basalt)	25.1	Very organic
Glamaig (granite)	21.7	Very organic
Lairig Ghru	6.1	Organic
Pass of Drumochter	23.6	Very organic
Glen Ogle 1	1.7	-
Glen Ogle 2	23.8	Very organic
Mill Glen	14.0	Organic

Table 6.3: Classification of samples based on organic content (BSI, 1999).

6.4 Permeability

The permeability of the sampled regolith from each site was analysed using a constant head permeameter to investigate the control of hydraulic transmissivity on the propensity of a hillslope to debris flow (table 6.4). The most permeable regoliths were found to be those at An Teallach and the Lairig Ghru with permeability coefficients (k) of 6.1 x 10^{-3} m s^{-1} and 4.3 x 10^{-3} m s^{-1} respectively. The Mill Glen regolith was found to be the least permeable with a permeability coefficient of 6.8 x 10^{-6} m s^{-1}. All of the permeability coefficients are typical for those expected for coarse sands, except for Mill Glen which has a permeability compatible with a fine sand (table 6.5).

Sample site	**Soil type** (BSI, 1981)	**Organic content** (%)	**Dry Density** (Mg m^{-3})	**Coefficient of Permeability** (**k**, m s^{-1})
An Teallach 1	Slightly silty SAND	1	1.54	6.1 x 10^{-3}
Glamaig (granite)	Silty SAND	21.7	0.99	2.1 x 10^{-4}
Glamaig (basalt)	Very silty SAND	25.1	0.76	1.2 x 10^{-4}
Lairig Ghru	Silty SAND	6.1	0.9	4.3 x 10^{-3}
Drumochter Pass	Silty SAND	23.6	0.62	1.3 x 10^{-3}
Glen Ogle 1	Very silty SAND	1.7	1.31	1.2 x 10^{-3}
Mill Glen	Very silty SAND	14	0.99	6.8 x 10^{-6}

Table 6.4: Permeability coefficients (k) of matrixes determined from constant head permeability tests.

Soil types	**Coefficient of Permeability (k,** m s^{-1}**)**
Gravels	> 1 x 10^{-2}
Coarse sands	1 x 10^{-5} to 1 x 10^{-2}
Fine sands	1 x 10^{-7} to 1 x 10^{-5}
Silts	1 x 10^{-9} to 1 x 10^{-7}
Clays	1 x 10^{-9} to 1 x 10^{-11}

Table 6.5: Range of coefficient of permeability (k) for different soil types (Selby, 1993).

6.5 Strength Parameters

The shear strength parameters of regolith matrix sampled from each study site are summarised in table 6.6 and the failure envelopes for the sampled matrixes are shown in figure 6.4. The critical friction angles (φ') of the tested regoliths ranged between 29.1º for the Drumochter Pass to 47.5º for Mill Glen. The critical apparent cohesions (c') ranged between 0 kPa for the Lairig Ghru and 3.7 kPa for the Glamaig (granite) and Mill Glen regoliths.

Despite the shear box tests being carried out at low effective stresses (2 – 13 kPa), only the stress-displacement results for the Glamaig (granite) and Mill Glen regolith matrixes displayed distinct values of peak stress, commonly associated with the dilation of granular materials during shearing. This indicates that the Glamaig (granite) and Mill Glen samples had denser initial packing of particles, whereas the stress-displacement results of the other samples are indicative of loose packing of particles (appendix A). The peak internal angle of friction and apparent cohesion for Glamaig (granite) and Mill Glen was found to be 46.8° and 6.1 kPa and 47.2° and 12.6 kPa respectively.

Dilation occurred in the tested specimens which displayed peak shear stress as well as in some of the tests carried out under the lowest normal stress (1.87 kPa) (appendix B). However, although the effective normal stresses in the shear box tests were low, (1.87 kPa – 12.77 kPa) compression, rather than dilation, occurred during the majority of tests. This was a consequence of the initial loose packing of the majority of the tested regoliths.

	Peak		Critical	
Sample	φ' (degrees)	c' (kPa)	φ' (degrees)	c' (kPa)
An Teallach 1	-	-	38	0.1
Glamaig (granite)	46.8	6.1	39.2	3.7
Glamaig (basalt)	-	-	32.1	0.8
Lairig Ghru	-	-	30.3	0
Drumochter Pass	-	-	29.1	0.8
Glen Ogle 1	-	-	42.7	1
Mill Glen	47.2	12.6	47.5	3.7

Table 6.6: Strength parameters of regolith samples tested in the small direct shear box.

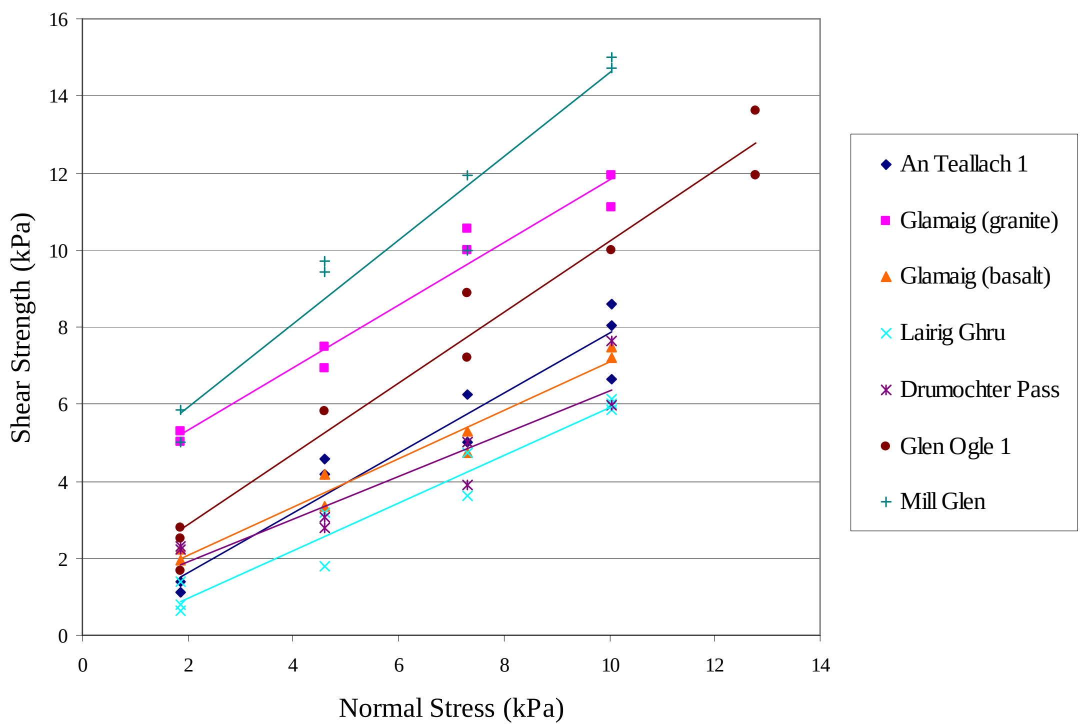


Figure 6.4: Shear strength envelopes for tested natural soils.

6.6 Summary

The particle size distribution of all sampled regolith matrixes are dominated by sand sized particles. There appears to be a lithologically forced determination on soil type amongst the sampled regoliths with sandstone yielding *slightly silty sands*, Granites and psammitic schists supporting *silty sands* and *very silty sands* developing over mica schists and extrusive igneous lithologies. All the soil matrixes have particles which display angularity. The most angular sample is Glamaig (granite), with a range of very angular to angular particles. The most rounded particles were observed in the soil matrixes at An Teallach which comprise sub-angular to sub-rounded particles. Both elongate and spherical particles were observed in the matrixes of the Glamaig (granite), Glamaig (basalt) and Lairig Ghru regoliths. At An Teallach particles are spherical in shape whilst both tabular and elongate particles were observed in the soil matrix in samples from Glen Ogle. The samples from Mill Glen and the Pass of Drumochter are characterised by a mixture of shapes with spherical, tabular and elongate particles observed in the samples. Based upon the classification of organic soils as outlined in BS 5930 (1999), the Lairig Ghru and Mill Glen samples have a “medium organic content” and are classified as *organic soils* whereas the samples from Glamaig, the Drumochter Pass and Glen Ogle 2 have a “high organic content” and are considered *very organic soils*. The regoliths sampled from An Teallach 1, An Teallach 2 and Glen Ogle 1 are not organic soils. The samples all have high permeabilities. The majority of the samples have permeability coefficients (k) compatible with those expected for coarse sands although the permeability of the Mill Glen sample is compatible with that expected for a fine sand

(Selby, 1993). The critical friction angles (φ') of the tested regoliths ranged between 29.1° for the Drumochter Pass to 47.5° for Mill Glen. The critical apparent cohesions (c') ranged between 0 kPa for the Lairig Ghru and 3.7 kPa for the Glamaig (granite) and Mill Glen regoliths.

7. Centrifuge Modelling of Hillslope Debris Flow Initiation

The majority of debris flows observed during field investigations were generated as shallow translational landslides which subsequently liquefied and made the transition from a sliding to a flow mass movement. In agreement with previous studies (e.g.: Ballantyne, 1981; Innes, 1982) this research has also indicated that there is a greater spatial frequency of debris flows on hillslopes mantled by soils with sandier matrixes yielded from coarse grained lithologies such as granite and sandstone compared to hillslopes with soils containing a larger silt component developed from finer grained schistose or extrusive igneous lithologies. A basic centrifuge model was proposed to investigate the susceptibility of coarse soils with varying particle size distributions to shallow translational landslide induced hillslope debris flows. Shallow transitional landslides were induced in loose, cohesionless laboratory soils by implementing a gradual increase in the phreatic surface. Soil water was monitored by pore pressure transducers with a view to quantifying critical pore water pressures and effective stress in each model soil. This chapter outlines the experimental method, centrifuge equipment and describes the results of the centrifuge tests.

7.1 Principle of Centrifuge Modelling

Centrifuge modelling has been widely utilised in research of geotechnical phenomena, and the theory and concepts of this investigative technique are detailed in various sources (Schofield, 1980; Craig, 1988; Taylor, 1995; Muir Wood, 2004). The basic principle of centrifuge modelling consists of recreating the same stresses applied to a full scale prototype in a small scale model. This is achieved by subjecting the model to a centrifugal acceleration which is greater than the Earth's gravitational field (g). Thus, centrifugal acceleration (N g) is applied to achieve replication in the reduced scale (1/N) model of unit stresses experienced through gravity in the full scale field prototype (1 g) (Taylor, 1995; Yun, 2006).

To ensure that prototype conditions are accurately represented in the centrifuge model, scaling relationships are derived to maintain the proportional influence of prototype parameters at the reduced scale (Stone & Merrien-Soukatchoff, 2007). A summary of basic scaling relationships for centrifuge modelling is shown in table 7.1. It is often difficult to sufficiently recreate prototype details in a small scale model and centrifuge modelling is also subject to significant scaling errors as a consequence of the non-uniform acceleration field. Consequently, it is important to acknowledge and fully understand the limitations of any given centrifuge model (Taylor, 1995).

As centrifuge modelling allows for the generation of stress levels in small scale models which match prototype values, it is well suited to simulating large scale mass movement events such as debris flows. Despite this, investigation of debris flows using geotechnical centrifuge technology is rare with previous research limited to prototype tests on propagation of granular debris flows in the Zurich drum centrifuge (Bowman *et al*. 2007) and the establishment of rainfall intensity/duration prediction curves (Ling & Wu, 2006). Modelling of debris flow initiation from shallow translational slides in soils with different particle size distributions as carried out in this research is unprecedented in the published scientific literature.

Parameter	**Unit**	**Scaling Factor**
Acceleration	$m\ s^{-2}$	N
Linear dimension	m	1/N
Stress	kPa	1
Strain	Dimensionless	1
Density	$Mg\ m^{-3}$	1
Mass or Volume	kg or m^3	$1/N^3$
Unit Weight	$kN\ m^{-2}$	N
Time (consolidation)	Sec	$1/N^2$
Force	N	$1/N^2$

Table 7.1: Scaling law relationships.

7.2 Centrifuge Test Apparatus

The centrifuge at the University of Dundee is a computer controlled beam centrifuge manufactured by Actidyn of France (figure 7.1). The centrifuge has an effective radius of 3.5 m and is equipped with a pendulum swinging platform able to accommodate a model with dimensions up to 0.8 m high and 1 m square contained within a strong box for placement and testing onboard the centrifuge. The maximum acceleration of the centrifuge is 130 times gravity with a 1 tonne payload.

Figure 7.1: The 7m diameter beam geotechnical centrifuge at the University of Dundee.

7.3 Model Design and Rationale

The hillslope debris flow centrifuge model was designed to simulate the initiation of a shallow translational landslide by gradually increasing the phreatic surface in a model slope comprised of laboratory soils with three different particle size distributions. The model consists of a rectilinear 30° “bedrock” slope of cemented sand and clay with a layer of laboratory soil at the crest of the slope 150 mm long, 100 mm wide and 20 mm thick (figure 7.2). The tests were undertaken at a scale of 1:100 and therefore carried out at a radial acceleration of 100g. Consequently, during testing the dimensions of the model slope represent a small prototype translational landslide 10 m wide by 15 m long with a soil depth of 2 m. The model soil depth of 2 metres is greater than any regolith mantle observed in the field during this research. However, debris flows triggered by shallow translational landslides up to 3 m thick have been recorded in Scotland (Innes, 1983b; Ballantyne, 2002a) and a 2 m thickness of laboratory soil permitted a greater variation in the phreatic surface during tests.

Three different model soils with varying silt contents were developed for testing. These were a *very silty sand* comprised of 80% fine lab sand and 20% HPF5 silt, a *silty sand* produced from a mix of 90% fine lab sand and 10% HPF5 silt and a soil comprised of 100% fine lab sand. The fractions of the model soils were chosen to approximately represent the range of particle size distributions of the natural soils sampled from the study sites in which the composition of fines (> 0.06 mm) ranged between 2.4% and 20.5% (see section 6.1). The three model soils were prepared by thoroughly mixing the desired compositions of sand and silt by hand to achieve homogeneity. The accuracy of the mixing technique was verified by laser granulometer tests. These showed that all of the model soils were dominated by the fine sand component with the largest particle sizes in each of the model soils being medium sand sized particles (no greater than 0.31 mm). The silt component in the *very silty sand* and *silty sand* was observed to be dominated by coarse silt particles (figure 7.3). A volume of material somewhat greater than was needed for each test was prepared and water was added to the dry model soil and mixed thoroughly to give an initial moisture content of 15%. The model soil was placed in the test at a density of 1.7 g cm^{-3}. This density was chosen in order to represent the loose nature of the regoliths encountered in the field.

The model slope angle of 30° was chosen as the gradient of source areas in Scotland is rarely lower than 30-32º (Ballantyne, 1981; Innes, 1982). A model slope gradient representing the general lower limit of hillslope debris flow initiation was selected in order to produce a higher initial safety factor. This allowed for a greater potential rise in the phreatic surface prior to failure and thus easier comparison of critical pore pressure values in the different model soil types. The model bedrock slope was constructed from a 75 % fine laboratory sand, 20 % china clay and 5 % cement mix. The sand was intended to provide frictional resistance between the model bedrock slope and the model soil, whilst the clay component ensured impermeability in the model bedrock to prevent water percolating away from the model soil into the cemented slope during testing. A steel strong box partition was developed to allow construction of the model slope in the middle of the strong box (figure 7.4). This was done to minimise the consequences of the centrifuge's radial acceleration field which results in the curvature of fluid surfaces during spin. The cement slope was constructed directly into the partition. 190ml of water per kilogram was added to the sand, clay, cement mix producing a dough-like consistency which was hand compacted into the partition using a wooden post and shaped into a 30° slope using a trowel before being left to harden.

During the tests, water was introduced into the model soil via a steel reservoir box which was built into the cemented bedrock slope. The reservoir box was fronted by a series of 5mm diameter holes which were covered by a sheet of wire gauze to prevent the model soil falling into the box. Water exited the model via a C-shaped steel drain built into the toe of the slope (figure 7.2; figure 7.5). Water was supplied to the reservoir through a 5 mm diameter flexible plastic pipe which ran along the centrifuge arm and down the centrifuge tower and was connected to the mains water supply via fluid slip rings (figure 7.6). The flow of water was controlled using a continuous cavity pump which was calibrated to ascertain the relationship between its voltage output and flow rate to allow for accurate manipulation of water levels in the model.

Variations in pore water pressure in the soil slope were monitored by three Pore Pressure Transducers (PPTs) (figure 7.7) placed at the interface between the cemented bedrock slope and the overlying soil slope. The PPTs were positioned equidistantly down the centre of the cemented slope at distances of 25 mm, 75 mm and 125 mm from the reservoir outlet (figure 7.2). The PPTs were numbered upslope to downslope from 1 to 3 for classification purposes. The transducers and associated wiring were contained in trenches carved into the cemented slope leading from the centre of the slope to the partition wall. This was done to ensure that the PPTs were kept in constant position in each test, to prevent them influencing the behaviour of the model soil slope and to protect the instruments from damage during slope failure. The dimensions of the trenches were just wide enough to contain the instruments and no more in order to minimise the effect on the interface frictional resistance. A fourth PPT was placed in the bottom of the reservoir box in order to monitor the head of water in the box. All of the PPTs were provided with an excitation of 5V D.C. and each transducer was calibrated to determine the relationship between its voltage output and engineering units (kPa). The behaviour of the model soils during the tests was also visually monitored using a small video camera mounted on the strong box and focused on the soil slope. The real-time images from the video camera were recorded on a video cassette.

A Labview computer programme was developed to allow control of water flow and monitoring of pore water pressure development during the tests from the centrifuge control room. Water flow rates were regulated using a dial control on the computer interface and PPT readings were shown on a graph of engineering units against time to allow for easy conceptualisation and manipulation of water levels during testing (figure 7.8). Throughout the tests output from the transducers and the continuous cavity pump was saved on the onboard centrifuge computer and stored in a series of text files. Post test analysis was carried out using an excel spreadsheet.

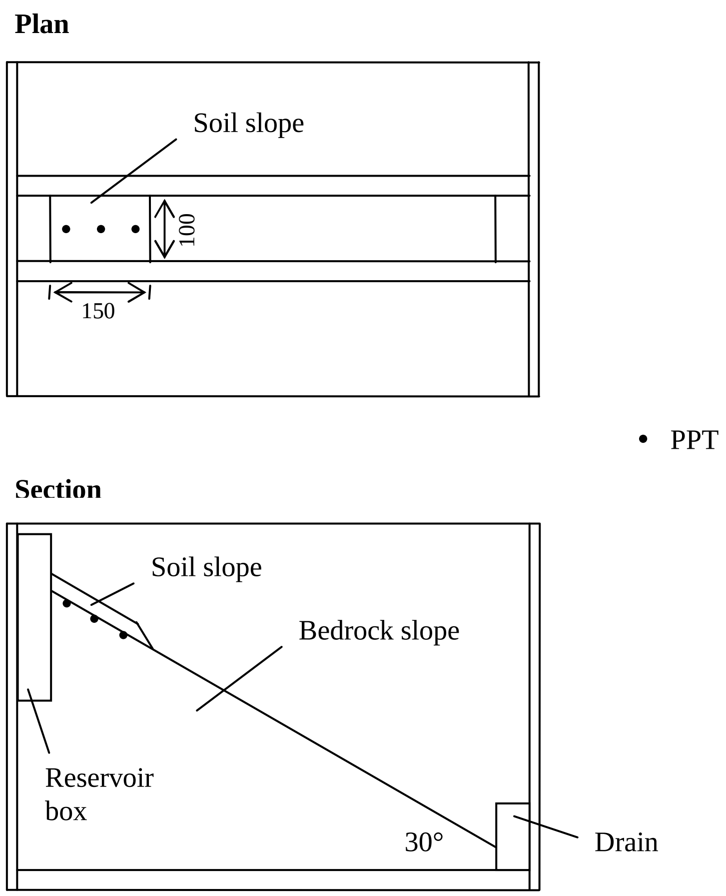


Figure 7.2: Components and dimensions of the hillslope debris flow centrifuge model.

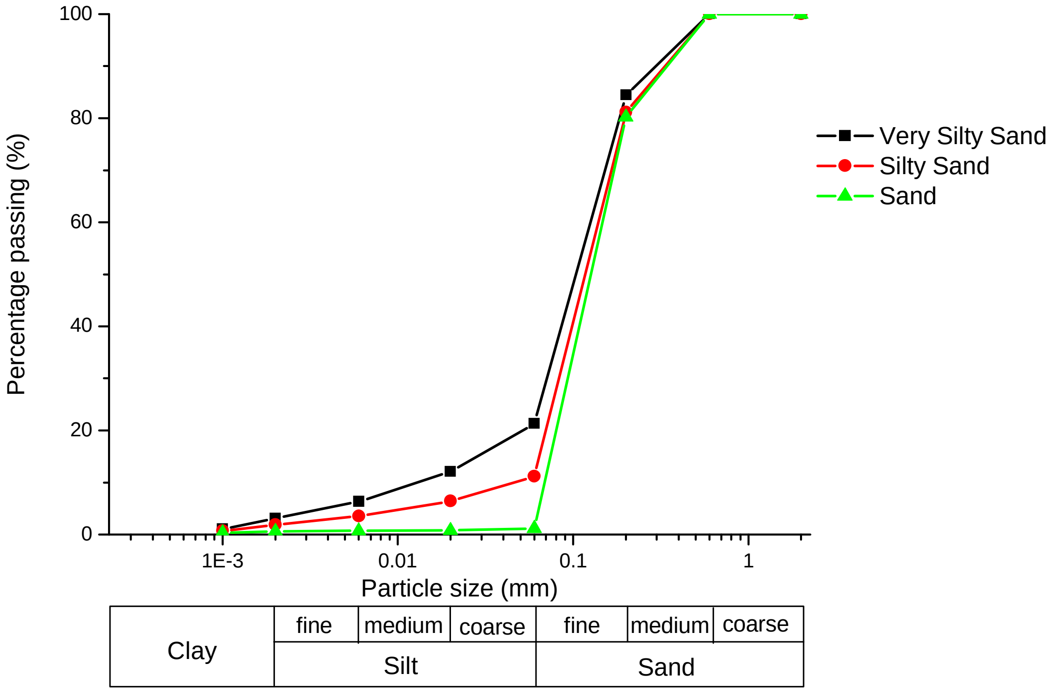


Figure 7.3: Particle size distribution of the three models soils used in the centrifuge tests.

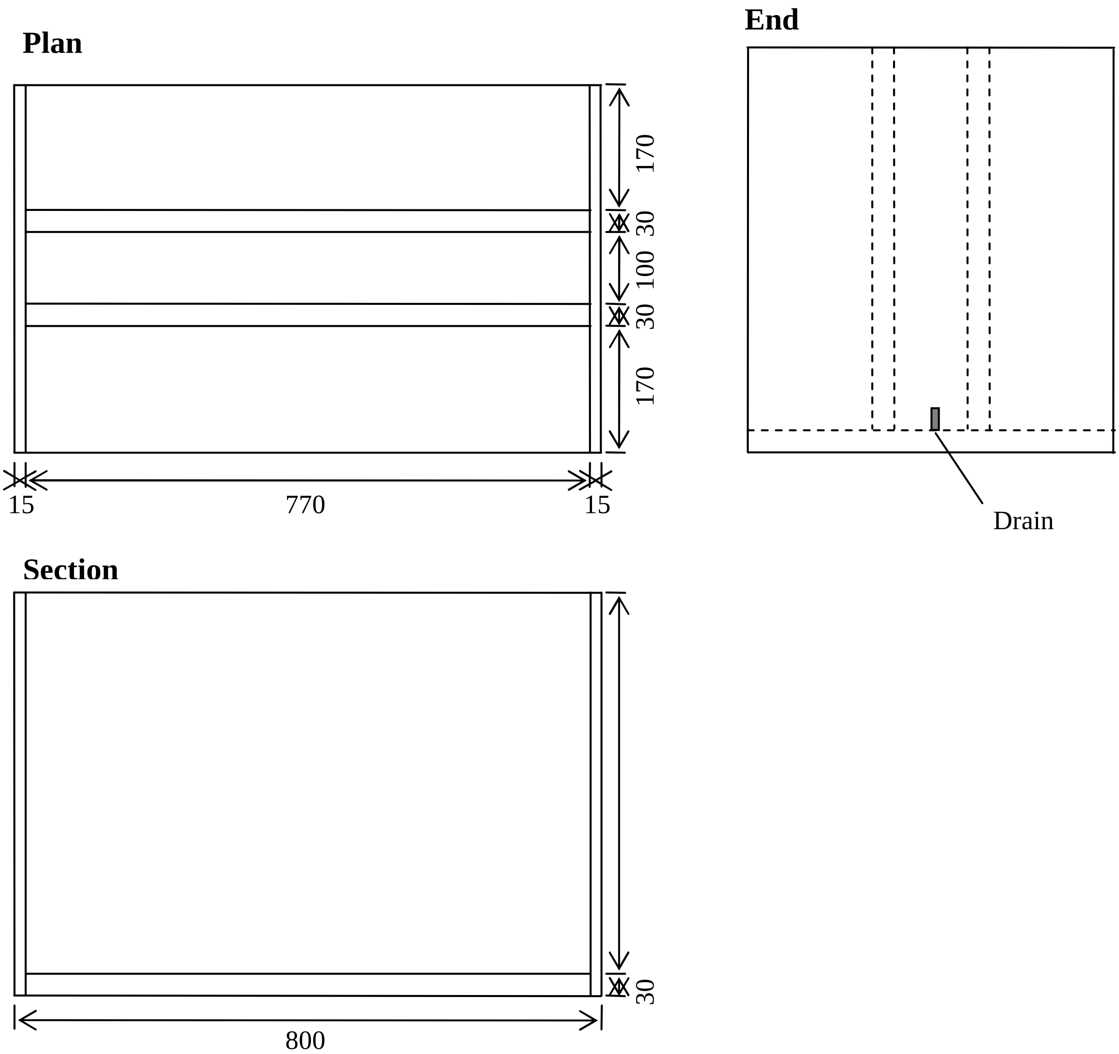


Figure 7.4: Dimensions of the centrifuge strong box partition.

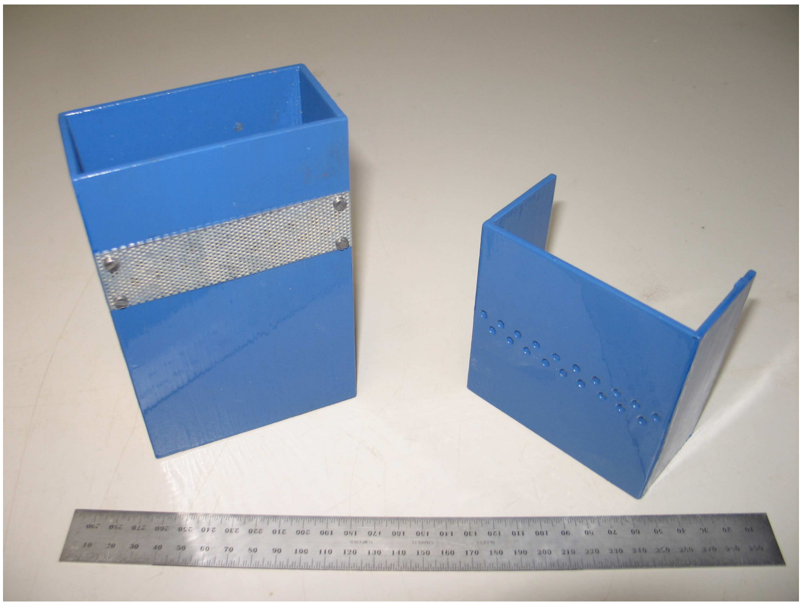


Figure 7.5: Reservoir box (left) and drain fixture before placement in centrifuge model.

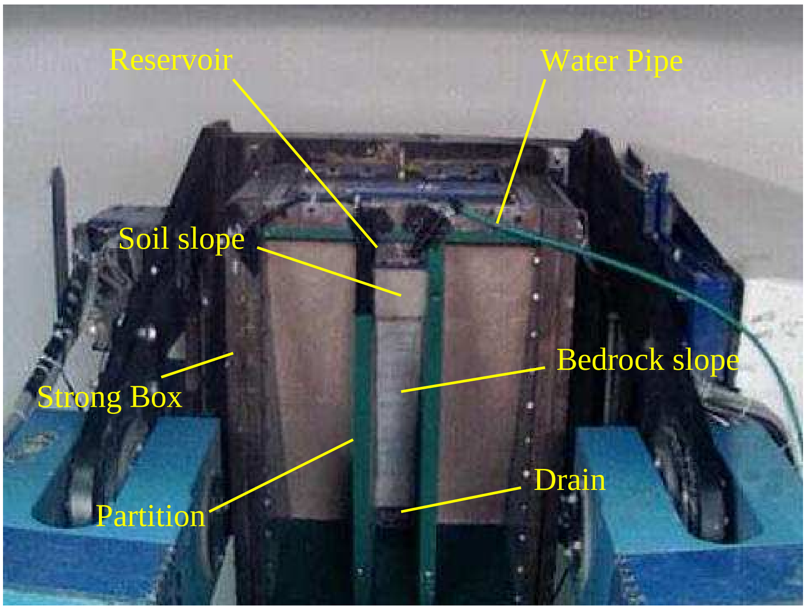


Figure 7.6: Plan view of model on centrifuge platform ready for testing.

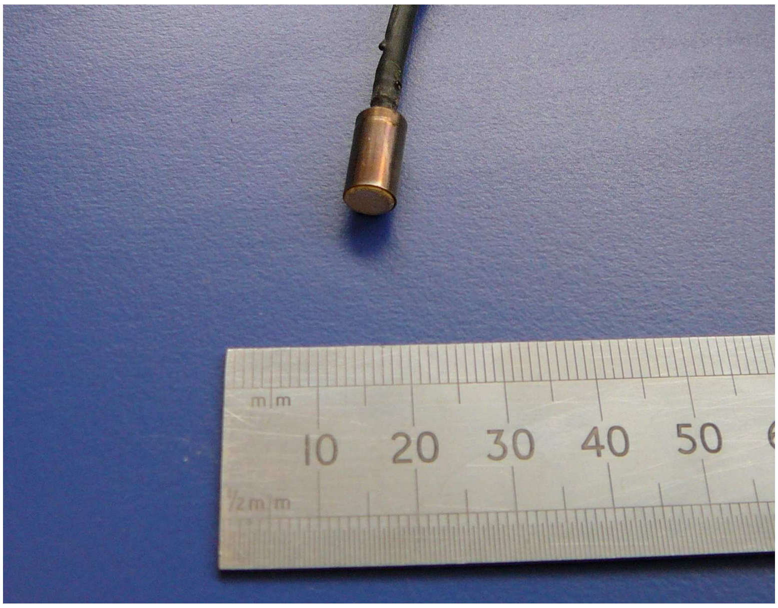


Figure 7.7: Photograph of pore pressure transducer (PPT).

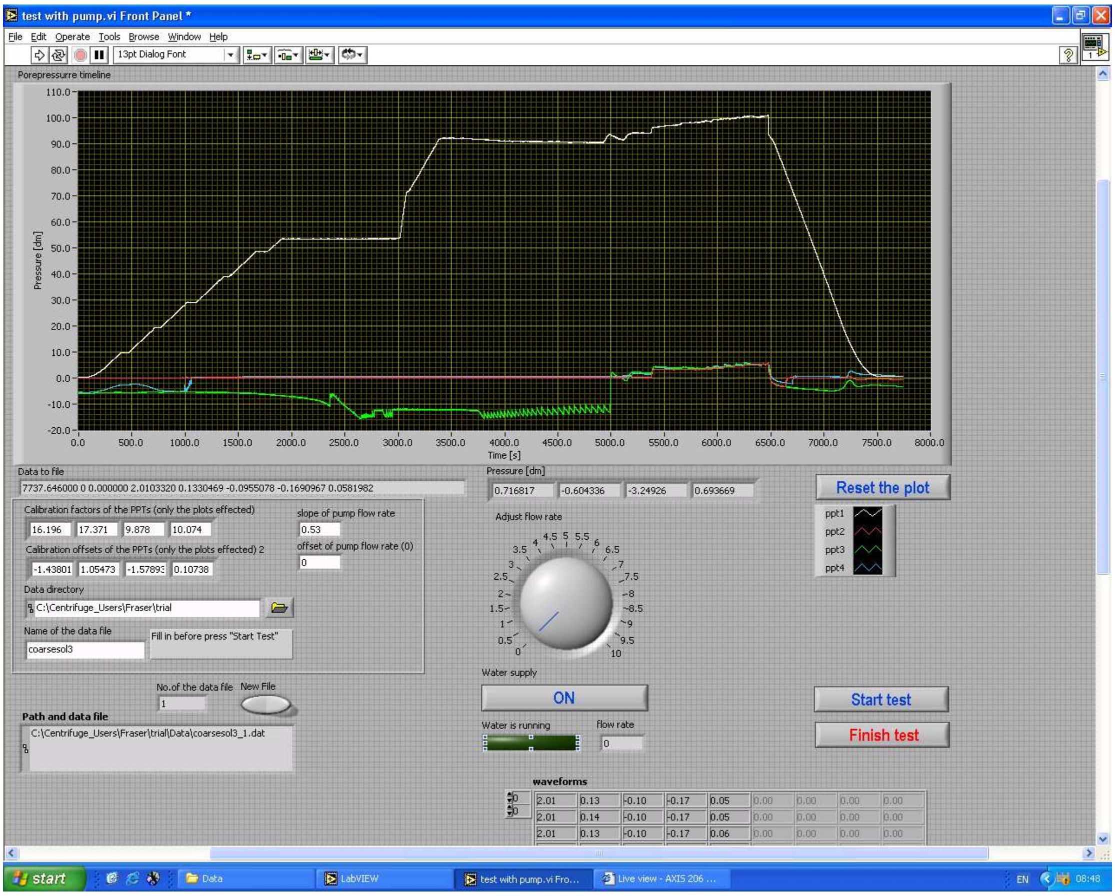


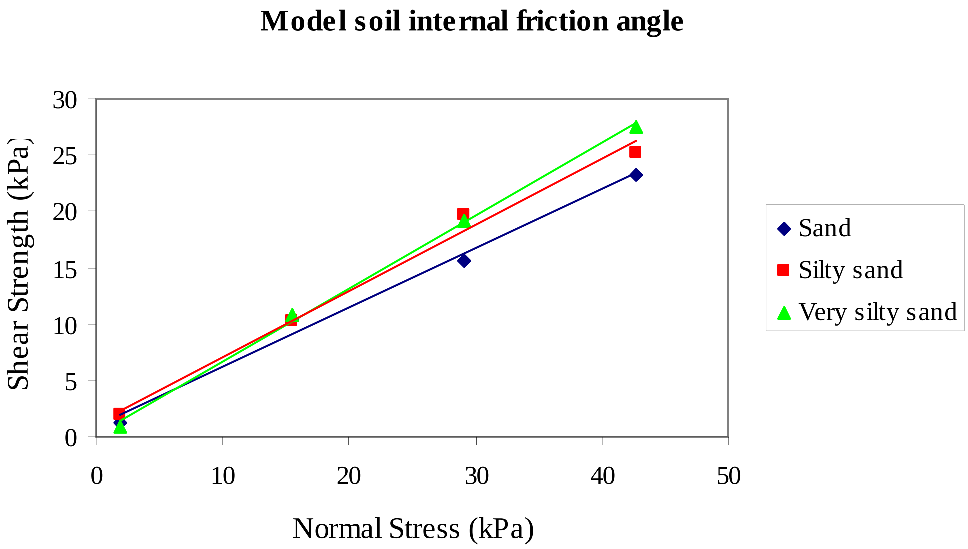
Figure 7.8: The Labview hillslope debris flow centrifuge test control room computer interface in operation.

7.4 Model Soil Properties

Several tests were carried out to determine the material characteristics of the model soils prior to commencement of the centrifuge testing programme. Effective stress strength parameters c' and φ' were obtained in drained small direct shear box tests in accordance with BS 1377 (BSI, 1990) (see section 4.2.2). The normal loads used in the tests were representative of the effective stress conditions experienced in the centrifuge model ranging between 2 kPa and 43 kPa. The tested model soil specimens were hand tamped into the shear box at a density of 1.7 g cm^{-3} with a water content of 15% to correspond with the initial soil conditions in the centrifuge tests. The angle of friction of the interface between the model soil and the model slope was also tested in the shear box. In order to do this a small 60 mm square and 20 mm high block of the cement slope mix was cast in a specially constructed mould and placed in the bottom half of the shear box. The model soils were then hand tamped on top of the cemented block. The split in the shear box corresponds with the interface and thus the maximum measured shearing resistance during the shear tests was representative of the soil-cement slope interface shear strength. The failure envelopes of the model soils are shown in figure 7.9 and the shear strength parameters are summarised in table 7.2. The critical friction angles (φ') of the model soils were found to be 27.6° for the *sand*, 30.2° for the *silty sand* and 33° for the *very silty sand*. The critical apparent cohesions (c') were 1 kPa for the *sand*, 1.3 kPa for the *silty sand* and 0.1 kPa for the *very silty sand*. The interface friction angles were found to be 30.4° for the *sand*, 31.8° for the *silty sand* and 30.9° for the *very silty sand* with interface apparent cohesions of 0.8 kPa for the *sand* and *silty sand*, and 2.2 kPa for the *very silty sand*. The lower internal friction angle in the sand can be explained in terms of the lower number of contact points in the uniformly graded fine laboratory sand (Selby, 1993). The internal and interface friction angles were only marginally above the model bedrock slope gradient. Consequently, infinite slope analysis (appendix C) indicated that the slopes all had relatively low initial safety factors and thus failure was liable to occur with increases in the phreatic surface ranging between 0 to 0.63 m during the centrifuge tests (table 7.3).

The relative density of the model soils was found to be 5.4% for the sand, 4% for the silty sand and 3.2% for the very silty sand indicating that the model soils were prepared and tested in a very loose state in the centrifuge model. The low relative densities of the samples also accounts for the occurrence of contraction, rather than dilation during shearing in all tests except those carried out under the lowest normal stress (1.9 kPa) (appendix D; appendix E). The shape of the model soil particles was determined by observation using a hand held lens. Coarser particles in the model soils were observed to have a dominantly rounded shape and high sphericity.

The permeability of the model soils was investigated using the constant-head permeability test following the procedures outlined in BS 1377 (BSI, 1990) using a specially constructed 51 mm diameter permeameter cell (see section 4.2.3). The coefficient of permeability (k) of each of the model soils are shown in table 7.4. The sand is the most permeable of the model soils with a permeability coefficient approximately 10 times greater than that of the very silty sand. The permeability of the silty sand is shown to be 6 times greater than the very silty sand. Thus, the permeability tests on the centrifuge model soils show a clear relationship between the proportion of silt sized particles and the coefficient of permeability with finer soils exhibiting lower permeabilities due to filling of void spaces by silt sized particles.



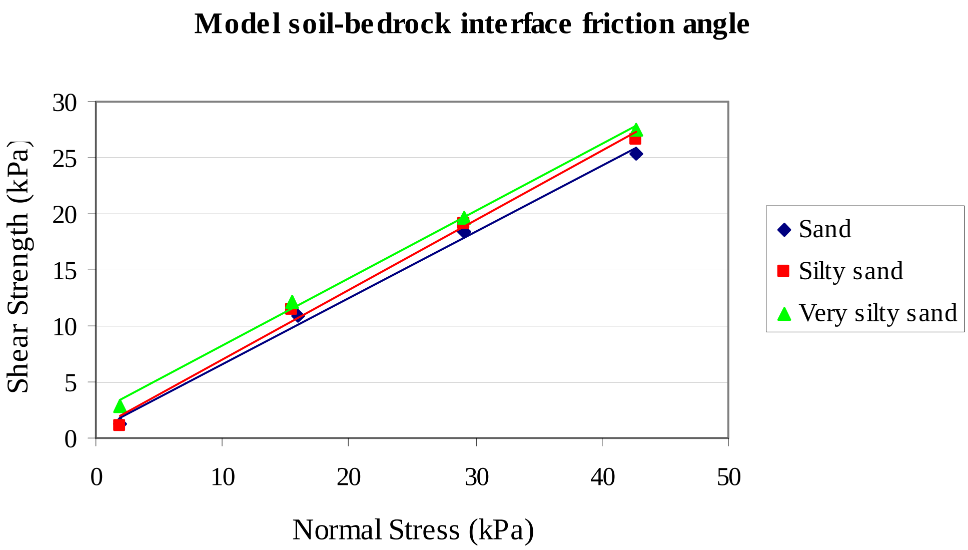


Figure 7.9: Failure envelopes of the three model soils.

	Internal		Interface	
Sample	**φ'** (degrees)	**c'** (kPa)	**φ'** (degrees)	**c'** (kPa)
Sand	27.6	1	30.4	0.8
Silty Sand	30.2	1.3	31.8	0.8
Very Silty Sand	33	0.1	30.9	2.2

Table 7.2: Summary of the strength parameters of the model soils.

	Internal		Interface	
Model Soil	**Fs, hw = 0**	**hw** (m)**, Fs = 1**	**Fs, hw = 0**	**hw** (m)**, Fs = 1**
Sand	0.97	0	1.07	0.29
Silty sand	1.1	0.34	1.13	0.42
Very silty sand	1.13	0.41	1.19	0.63

Table 7.3: Safety factors (Fs) for the model soils determined from infinite slope analysis and height of water in soil required to create instability (Fs = 1).

Model Soil	**Coefficient of Permeability (k)** (m s^{-1})
Sand	1.1×10^{-3}
Silty sand	6.8×10^{-4}
Very silty sand	1.4×10^{-4}

Table 7.4: Coefficient of permeability of the model soils.

7.5 Centrifuge Test Procedure

The centrifuge test programme consisted of a total of nine centrifuge tests consisting of three tests on each of the three model soil types. The test procedure including preparation of the model and the centrifuge for testing, in flight routine and the post-test course of action is outlined below.

7.5.1 Test preparation

The partition containing the cemented bedrock slope was placed in the strong box which in turn was placed on the centrifuge gondola. The water system was checked for blockages and leaks and to ensure the pump was functioning correctly. The water pipe was then connected to the model reservoir. The video camera was connected and adjusted to allow for observation of slope behaviour from real time images obtained during centrifuge flight. 20mm wide, 150 mm long strips of sandpaper were attached to the walls of the partition at the top of the model slope before each test prior to placement of the model soil. This was done to avoid preferential failure of the soil slope at the partition wall by increasing frictional resistance and preventing higher water flows and peripheral erosion at the soil-partition interface. The PPTs were connected and checked to ensure they were functioning correctly and placed in the slope immediately prior to applying the model soil to prevent the porous stone drying out (figure 7.10). The PPT wiring was firmly taped down to prevent any movement during centrifuge flight. A wooden support was constructed to allow the model soils to be hand tamped directly on to the model slope (figure 7.11). In order to maintain homogeneity, the model soil was tamped in four layers. The centrifuge test was commenced as quickly as possible after placement of the model soil slope in order to minimise the drying out time experienced by the model soil.

7.5.2 In-flight procedure

The centrifuge was accelerated so that 100g was exerted on the centre of the model soil slope. It took approximately 30 minutes to reach the desired acceleration. The water supply was then switched on and the reservoir box was filled up to the level of the outlet. The water was then allowed to slowly percolate into the model soil, initially using a low flow rate (*c*.21 ml min^{-1}) which was gradually increased in order to generate a steady increase in the phreatic surface until slope failure was induced. Failure is taken as the point in the test where the model slope experiences extensive flow mass movement which subsequently propagates down the model slope away from the source area. After debris flow initiation the centrifuge was decelerated and stopped.

7.5.3 Post-test procedure

Following completion of the test, the data was saved and backed up. The model bedrock slope was cleaned up and the drain at the foot of the slope was cleared of sediment. Any intact material remaining in the source area at the top of the model slope was carefully removed and weighed to allow calculation of the mass of material that was involved in the simulated mass movement. The PPTs were removed from the model and de-aired over night in a vacuum chamber for use in subsequent testing.

Figure 7.10: Placement of pore pressure transducers in custom made trenches in the model bedrock slope immediately prior to placement of model soil.

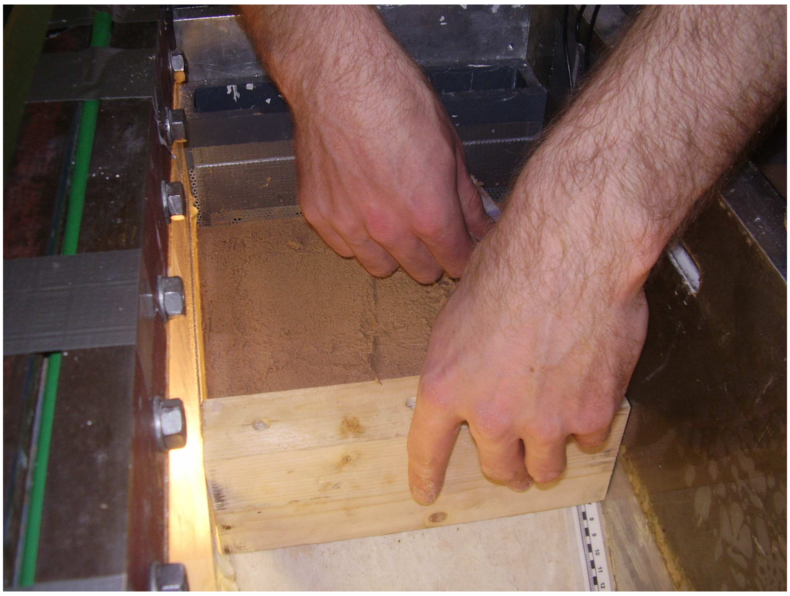


Figure 7.11: Placement of model soil slope by hand tamping and with use of a wooden support.

7.6 Centrifuge Test Results

The progress of each test was observed using real time images relayed to the control room from a small video camera mounted on the strong box and focused on the model soil slope. In all tests, the soils were observed to have liquefied immediately upon failure. This was a consequence of all the soils being loose, contractive soils (Gabett & Mudd, 2006). In all cases only a portion of the soil slope failed leaving a small failure scar on the soil slope (figure 7.12) with the failure plane occurring at or just above the interface with the model bedrock slope. The volume of soil left in the source area subsequent to the test was weighed to indicate the mass of material that had passed down slope during the test thus allowing inferences to be made on the scale of the simulated mass movements. It was found that the mass of material that passed down slope was similar for all the tests, indicating that there was no difference in the scale of debris flows simulated in soils with different particle size distributions (figure 7.13). The mode of failure was characterised by a sudden, extensive flow mass movement in the model soil slopes consisting of silty sand and very silty sand. However, the sand tests were characterised by regressive slope failures in which several small flows involving approximately 3 to 6 m^3 of material propagated upwards from the lower portion of the slope before a final, larger scale mass movement *c*. 30 m^3 to 50 m^3 in volume occurred in the upper portion of the slope. The majority of failures were initiated preferentially to the right side of the model soil slope. This may reflect an increased interface frictional resistance caused by the presence of the PPT trenches on the left flank of the slope. The presence of the PPT wires taped to the side of the partition wall may have also locally increased the frictional resistance of the soil on the right side of the soil slope.

The variation in the phreatic surface and effective stress during each of the tests is shown in figures 7.14, 7.15 and 7.16. The general trend in each test is characterised by a gradual rise in the phreatic surface, with the point of failure being demarked by a sudden drop in pore pressures as slope failure is initiated and the model soil flows downslope. The stepped nature of the graphs is symptomatic of the pump-controlled gradual increase in the rate of water ingress into the model soil. The pattern of water ingress into the soil for each test is shown in figure 7.17. The critical values recorded immediately prior to failure in each test are summarised in terms of the height of the phreatic surface and the effective stress in table 7.5. This data is used to assist in the comparison of the sensitivities of each tested soil type to increases in pore water pressures.

In the sand tests the phreatic surface at the point of failure was up to 0.51 m, 0.5 m and 0.57 m high for sand tests 1, 2 and 3 respectively, although higher values of 0.54 m in sand test 1, 0.55 m in test 2 and 0.59 m in test 3 were achieved earlier in the tests prior to debris flow initiation. The effective stresses were reduced from 34 kPa when $u = 0$, to 28.9 kPa, 29 kPa and 28.3 kPa for sand tests 1, 2 and 3 respectively (table 7.5; figure 7.14). The profile of the water table during the sand tests show that PPTs 2 and 3 have higher values than PPT 1 for much of the tests. This is particularly the case in sand test 2 and test 3. As the water rate was increased the phreatic surface became uniform and rectilinear in profile before failure was generated. This observed lag in the height of the phreatic surface above PPT 1 is a function of the high permeability of the sand resulting in a rapid, gravity induced dissipation of water away from the upper slope at lower flow rates.

At the point of slope failure in the silty sand tests the height of the phreatic surface was up to 0.88 m in test 1, 0.7 m in test 2 and 0.54 m in test 3. This is equivalent of a reduction in effective stress from 34 kPa when there is no phreatic surface, to 25.2 kPa, 27 kPa and 28.6 kPa respectively (table 7.5: figure 7.15). In silty sand test 2 the phreatic surface achieved a maximum height of 0.82 m earlier in the test prior to debris flow initiation whereas in test 1 and 3 the maximum phreatic surface was reached at the point of failure. In silty sand tests 1 and 2, PPT 2 registered the highest pore pressure reading. This indicates a lag in the flow of water through the slope resulting in a higher phreatic surface in the middle slope reflecting the slightly lower permeability of the silty sand compared to the 100% sand model soil.

In the tests on the very silty sand, the phreatic surface was observed to rise up to 1.11 m in test 1, 1.12 m in test 2 and 0.96 m in test 3. This was equivalent of reduced effective stresses from 34 kPa (u = 0) to 22.9 kPa, 22.8 kPa and 24.4 kPa respectively (table 7.5, figure 7.16). In very silty sand test 2 and test 3, the highest phreatic surface was recorded above PPT 1 with a downward gradient in phreatic surface downslope recorded in PPT 2 and PPT 3.

The values recorded from the PPTs in each test were averaged to give the mean phreatic surface and effective stress experienced in the model soils. The variations in the mean phreatic surface and effective stress during the tests are shown in figure 7.18 and the average phreatic surface and effective stress immediately prior debris flow initiation in each test is shown in table 7.6. It is apparent from the pore pressure data that the very silty sand can accommodate a greater increase in pore water pressures and a greater reduction in effective stress before failure is initiated compared to the slopes comprised of 100% sand. The critical increases in pore pressure in the silty sand tests fall between those measured in the sand and very silty sand tests. The silty sand test 1 attains a mean phreatic surface just below the lowest mean phreatic surface experienced in the very silty sand tests (very silty sand test 1), whereas silty sand test 3 reaches an average phreatic surface comparable to the sand tests. The average effective stresses immediately prior to failure were reduced to 29.3 kPa, 29.3 kPa and 28.5 kPa in the sand tests, 26.2 kPa, 27.6 kPa and 29.1 kPa in the silty sand tests and 26.1 kPa, 25.8 kPa and 24.9 kPa in the very silty sand tests. This is equivalent to a mean reduction in effective stresses from 34 kPa when the height of the phreatic surface is 0m in all of the model soils by 4.7 kPa, 4.8 kPa and 5.8 kPa in the sand tests, 6.4 kPa, 4.9 kPa and 7.8 kPa in the silty sand tests and by 7.9 kPa, 8.2 kPa and 9.1 kPa in the very silty sand soil tests. During some tests it is apparent that the phreatic surface reached a higher level earlier in the test than that which eventually triggered slope failure (figure 7.14; figure 7.15; figure 7.16; figure 7.18). This is the result of a combination of transient non-uniformities in the phreatic surface immediately following increased water ingress and soil ripening, in which the strength of the soil slope was reduced as the test progressed due to the erosive effects of throughflow.

Different rates of water ingress were required to increase the pore pressures to the critical levels that caused failure in each test (figure 7.17; table 7.7). The model slopes comprised of 100% sand required the highest rates of water ingress to initiate failure ranging between 107.1 – 133.9 ml min^{-1}compared to 75 and 85.7 ml min^{-1} in the silty sand tests and 48.2 and 58.9 ml min^{-1} in the very silty sand tests. Thus, the coarser the texture of the soil, the higher the flow rate was required to increase pore pressure to critical levels. This trend is a function of the higher permeability of the coarser soils which results in the soil draining more quickly. Consequently, the volume of water used in the sand tests was generally greater than that used in the silty sand and very silty sand tests (table 7.7).

Figure 7.12: Typical failure scar in model soil slope after test.

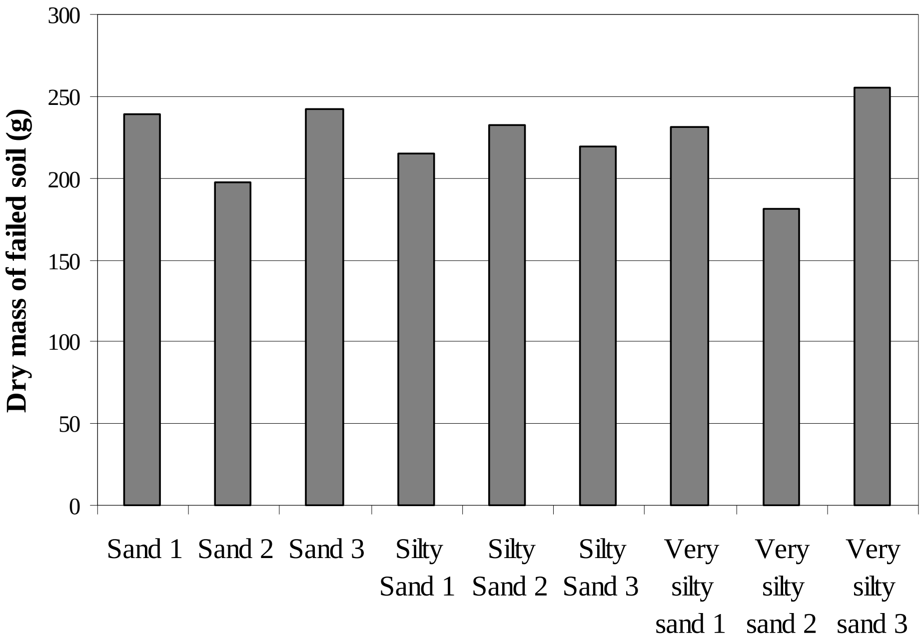


Figure 7.13: Bar chart showing mass of failed material in each test.

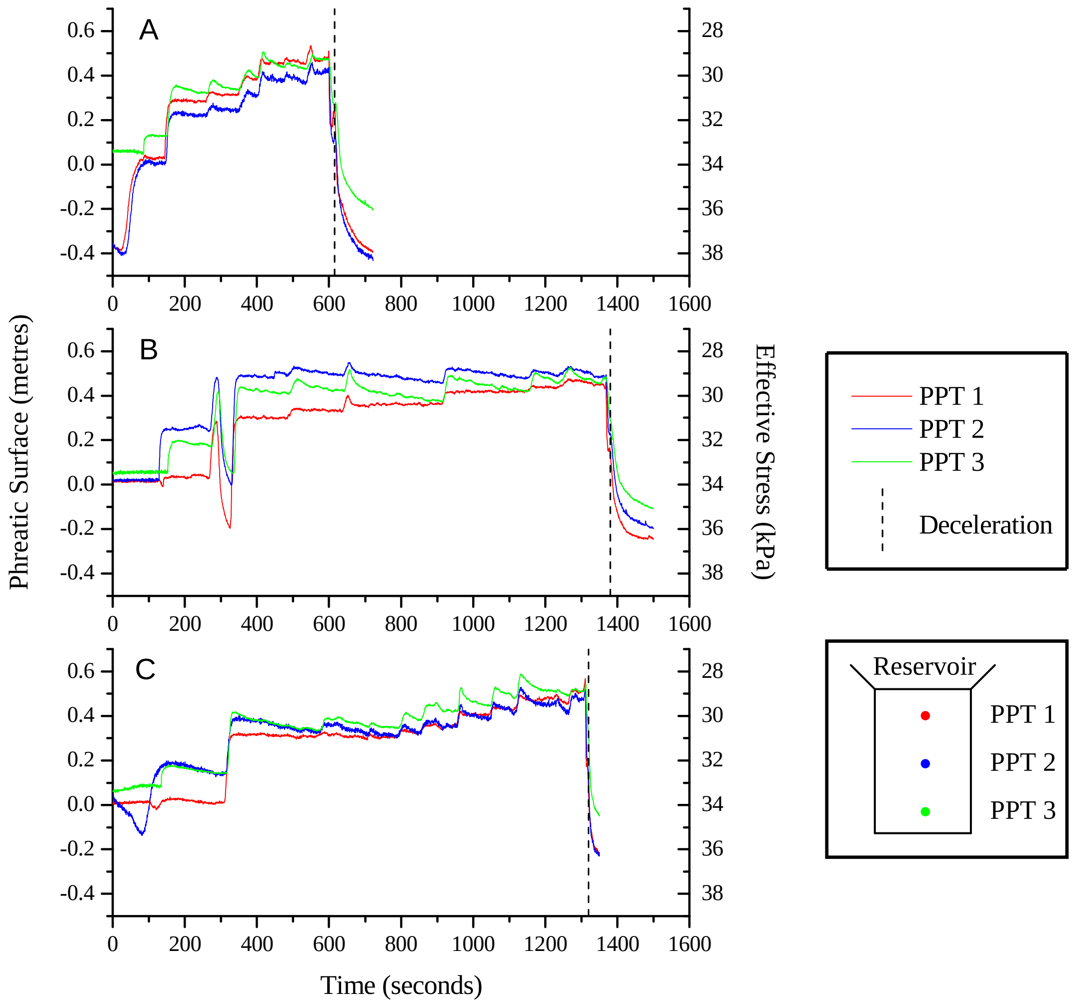


Figure 7.14: Variation in the phreatic surface and effective stress during the tests on model soil slopes comprised of 100% fine lab sand.

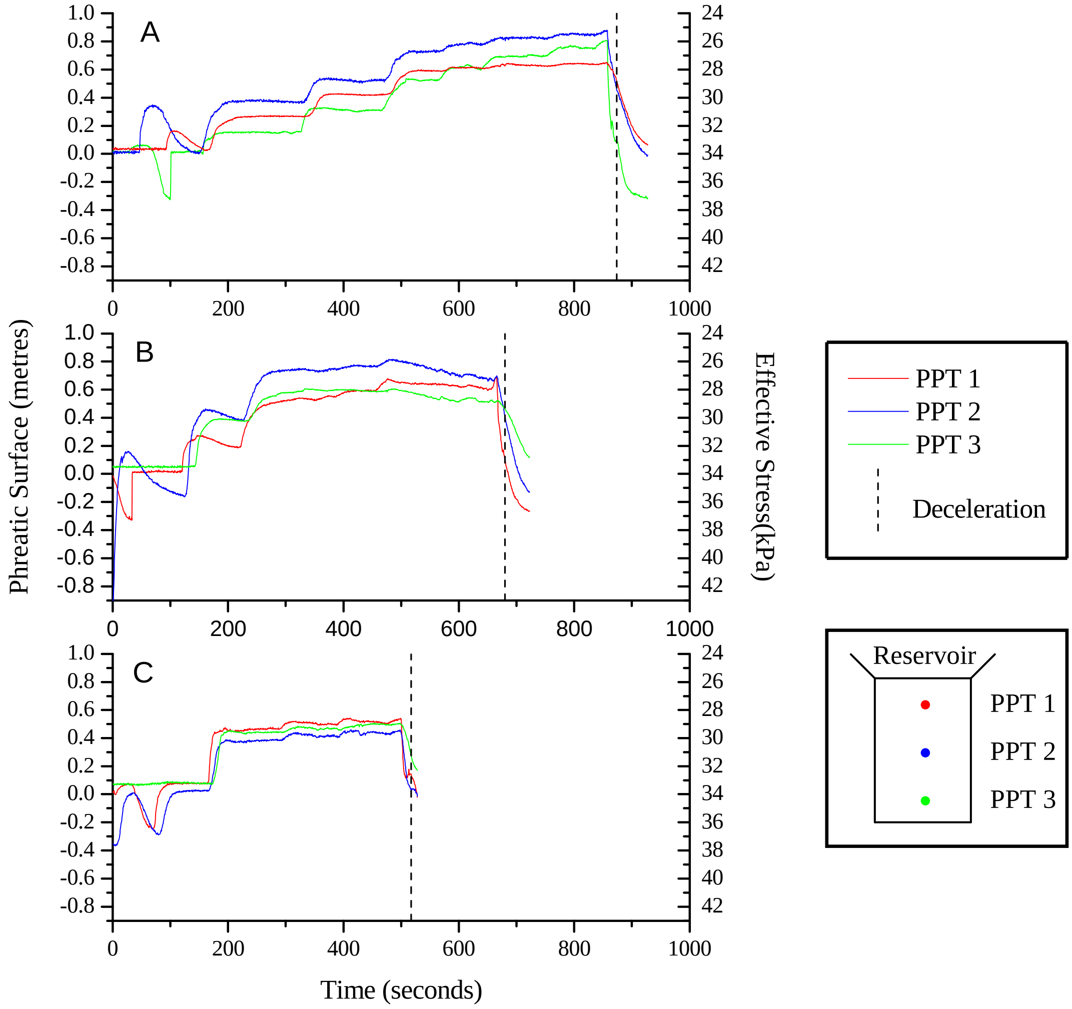


Figure 7.15: Variation in the phreatic surface and effective stress during the tests on model soil slopes comprised of silty sand.

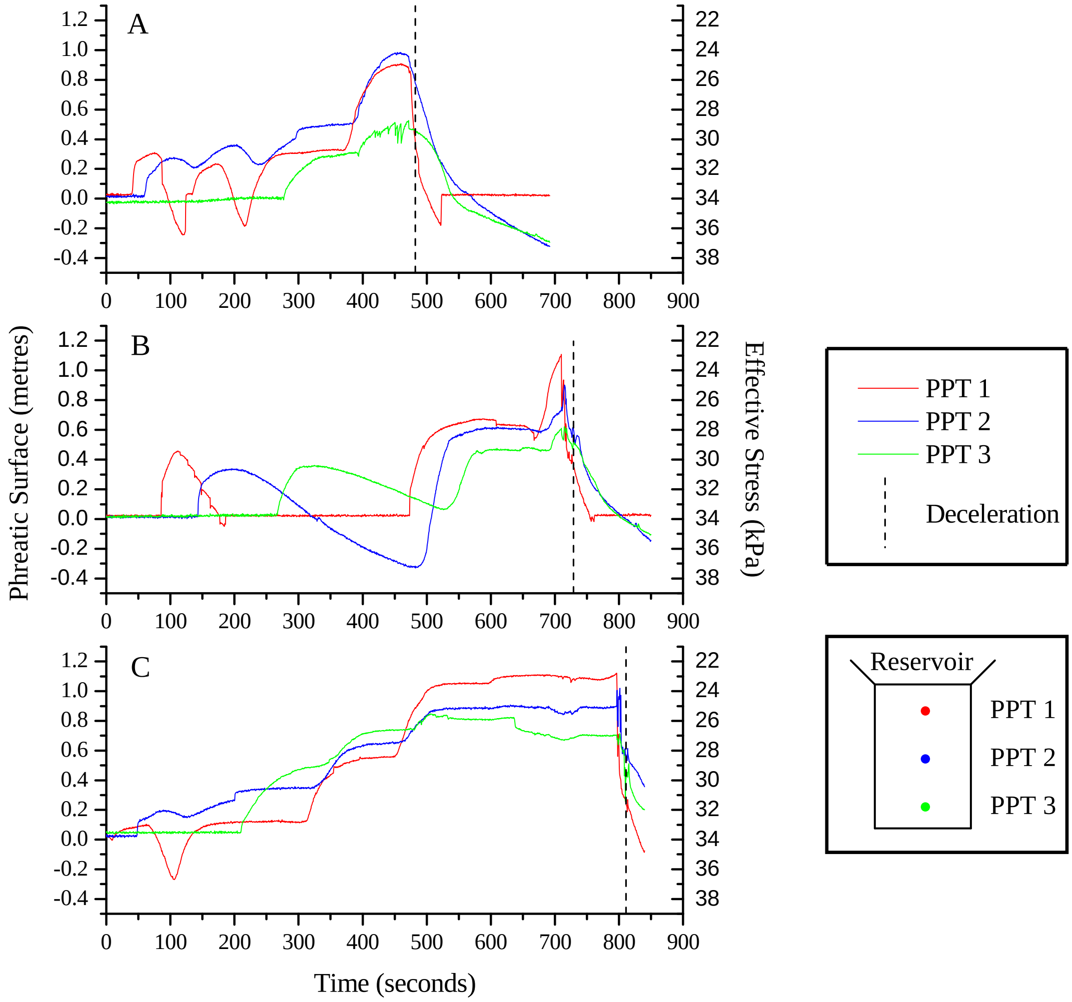


Figure 7.16: Variation in the phreatic surface and effective stress during the tests on model soil slopes comprised of very silty sand.

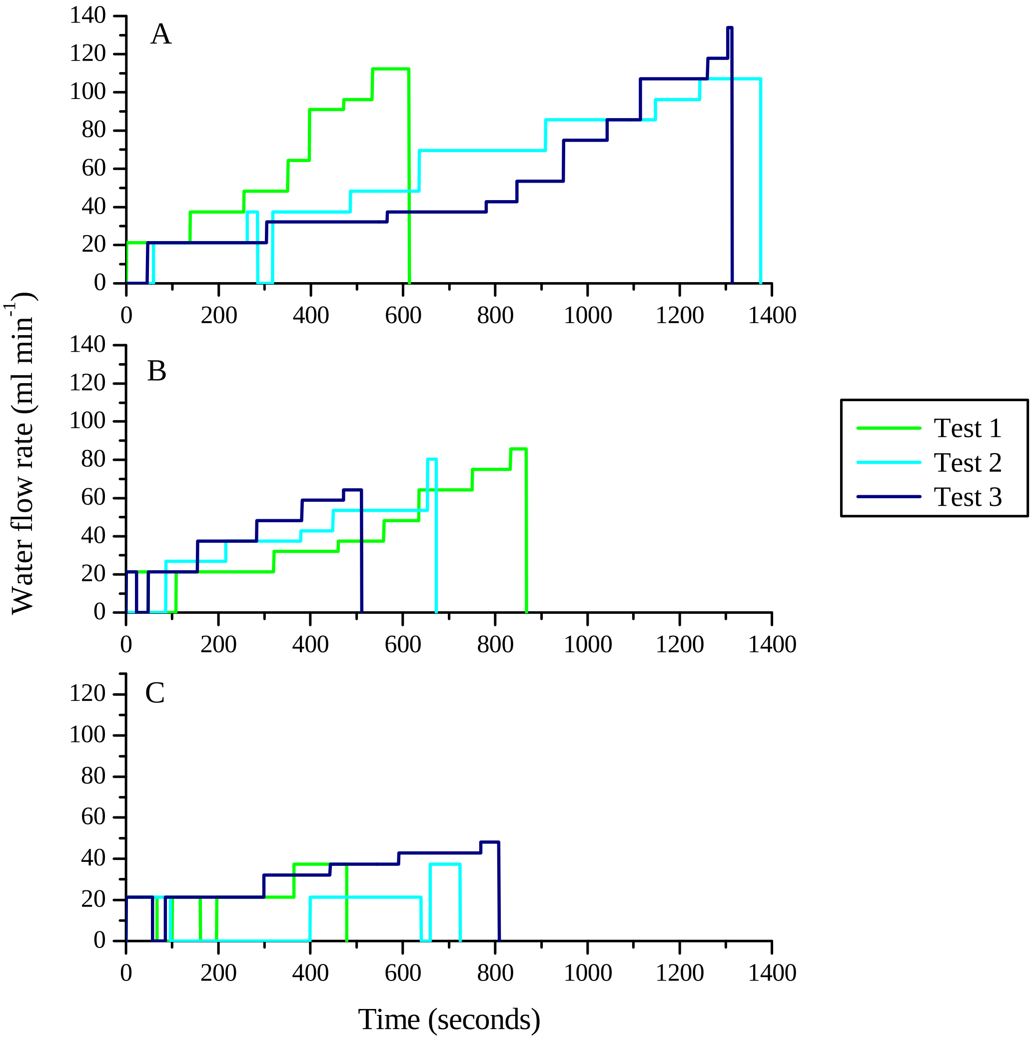


Figure 7.17: The pattern of water ingress into the model soil slope for the sand tests (A), the silty sand tests (B) and the very silty sand tests (C).

	Phreatic Surface (metres)			Effective Stress (kPa)		
Test	**PPT 1**	**PPT 2**	**PPT 3**	**PPT 1**	**PPT 2**	**PPT 3**
Sand 1	0.51	0.44	0.47	28.9	29.6	29.3
Sand 2	0.46	0.5	0.48	29.4	29	29.2
Sand 3	0.57	0.54	0.55	28.3	28.6	28.5
Silty Sand 1	0.81	0.88	0.65	25.9	25.2	27.5
Silty Sand 2	0.69	0.7	0.52	27.1	27	28.8
Silty Sand 3	0.54	0.46	0.5	28.6	29.4	29
Very Silty Sand 1	0.89	0.96	0.53	25.1	24.4	28.7
Very Silty Sand 2	1.11	0.9	0.61	22.9	25	27.9
Very Silty Sand 3	1.12	1.02	0.71	22.8	23.8	26.9

Table 7.5: Phreatic surface and effective stress values recorded by each pore pressure transducer immediately prior debris flow initiation in each test.

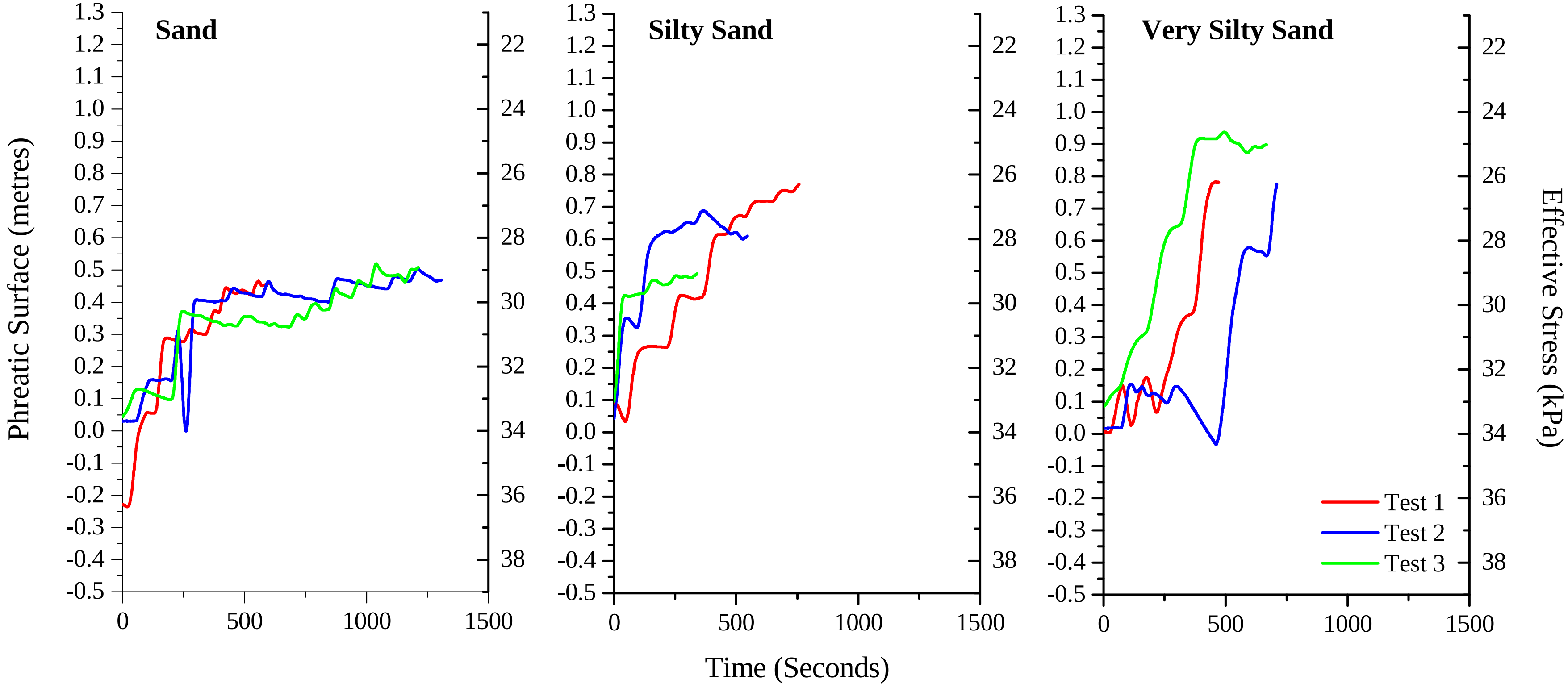


Figure 7.18: Variations in the mean phreatic surface and effective stress in each of the tests.

Test	Mean Phreatic Surface at Failure (m)	Mean Effective Stress at Failure (kPa)	Reduction in Effective Stress kPa (34 kPa when u = 0)
Sand 1	0.47	29.3	4.7
Sand 2	0.48	29.2	4.8
Sand 3	0.55	28.5	5.5
Silty sand 1	0.78	26.2	7.8
Silty sand 2	0.64	27.6	6.4
Silty sand 3	0.49	29.1	4.9
Very silty sand 1	0.79	26.1	7.9
Very silty sand 2	0.82	25.8	8.2
Very silty sand 3	0.91	24.9	9.1

Table 7.6: Average phreatic surface and effective stress immediately prior debris flow initiation and reduction in effective stress in each test.

Test	Duration of Water Flow (seconds)	Maximum Flow (ml min^{-1})	Volume of Water (ml)
Sand 1	619	112.5	590.6
Sand 2	1329	107.1	1371.4
Sand 3	1383	133.9	1230.1
Silty Sand 1	882	85.7	553.9
Silty Sand 2	599	80.3	425.9
Silty Sand 3	527	75.0	334
Very Silty Sand 1	480	53.6	177.1
Very Silty Sand 2	727	58.9	146.9
Very Silty Sand 3	825	48.2	433.6

Table 7.7: The duration of water flow, maximum flow rate and total volume of water used in each test.

7.7 Summary

A centrifuge model was developed to investigate the susceptibility of coarse soils with varying particle size distributions to shallow translational landslide induced hillslope debris flows. Shallow transitional landslides were triggered in loose, cohesionless laboratory soils by implementing a gradual increase in the phreatic surface with water pressures during tests monitored using pore pressure transducers. The results show that the very silty sand can accommodate a greater increase in pore water pressures and a greater reduction in effective stress before failure is initiated compared to the slopes comprised of 100% sand. Different rates of water ingress were required to increase pore pressures to levels sufficient to trigger slope failure in each test. The model slopes comprised of 100% sand required the highest rates of water ingress to initiate failure ranging between 107.1 – 133.9 ml min^{-1} compared to 75 and 85.7 ml min^{-1} in the silty sand tests and 48.2 and 58.9 ml min^{-1} in the very silty sand tests. Thus, the coarser the texture of the soil, the higher the flow rate was required to increase pore pressure to critical levels. This trend is a function of the higher permeability of the coarser soils which results in the soil draining more quickly. Consequently, the volume of water used in the sand tests was generally greater than that used in the silty sand and very silty sand tests.

8. Interpretations

Topographic and material controls on the debris flow process at six study sites in upland Scotland have been investigated using a combination of field work, laboratory analysis and centrifuge modelling. The results of these investigations are interpreted in this chapter.

8.1 Field observations and measurements

The spatial densities of debris flow measured at each study site indicate that hillslopes underlain by sandstone and granitic bedrocks have a greater spatial frequency of flows than those underlain by schist and extrusive lava bedrocks (table 5.1; figure 5.1). These results are in agreement with observations from previous research (Ballantyne 1986; Innes, 1983b; Curry, 1998, 2000a). This trend largely persists when the data is normalised for site specific average annual rainfall totals despite the fact that the study site locations underlain by granite and sandstone have higher average annual rainfall totals and can accordingly be considered meteorologically more predisposed to debris flow activity. However, it was found that the normalised debris flow density at Drumochter, a site with a schistose lithology, is slightly greater than An Teallach which is underlain by Torridonian Sandstone. This is most likely the consequence of both the relatively coarse nature of regolith yielded from psammitic schist (Innes, 1986) and sediment supply issues that are discussed in greater detail later in this section.

It has been hypothesised that slopes underlain by granites and sandstones generally support a greater spatial density of debris flow as they yield coarser, sandier matrixes with higher permeabilities which allow rapid increases in pore water pressures during rainstorms (Innes, 1982; Ballantyne, 1986). However, observations in this research have shown that the spatial frequency of debris flow is also strongly influenced by slope geometry and morphology. Higher debris flow densities tend to occur at sites where the topography is characterised by rectilinear or concave profiles with persistently steep upper slopes and a high incidence of potential debris flow source areas in the form of depressions, gullies and couloirs often amongst rocky crags. Steep upper slopes result in greater shear stresses whilst depressions, gullies and couloirs facilitate a morphologically controlled, gravity induced concentration of hillslope runoff and subsurface drainage leading to soil saturation, reduced effective stress and instability. Such a topographic predilection for high debris flow density is apparent at the Lairig Ghru and Glamaig study sites. At Glamaig this results in a markedly higher actual debris flow density on the basalt side of the mountain than that experienced at the other study sites with fine grained extrusive igneous or schistose lithologies. At the Glamaig and Lairig Ghru study sites the studied hillslopes are heavily scarred by debris tracks with almost every identifiable potential source area having yielded a discernable (relatively recent) debris flow. It can therefore be inferred that it is likely these study sites have reached a maximum spatial density of debris flow activity.

The lowest debris flow spatial densities were measured at Glen Ogle and Mill Glen. At Glen Ogle all of the observed debris flows were generated on the 18th of August 2004. However, previous research has identified landslide scars on aerial photographs from the 1940s and 1950s that are no longer clearly discernable in the field or on more recent aerial photographs (Wilson, 2006). Visits to the study site in the years subsequent to the 2004 event have also shown quick colonisation of debris deposits and landslide scars by vegetation, rapidly reducing the visibility of debris flow forms. Alternatively, debris flow deposits at the Lairig Ghru study site dating from the late 1970s were observed to have become only partially vegetated indicating a much longer period of vegetation colonisation in excess of 30 years. Therefore, the low debris flow density measured in the field at Glen Ogle may partially be a function of the relative rapidity of vegetation colonisation compared to other study sites.

At Mill Glen study a high frequency of shallow hillslope gullies was observed (figure 5.46). These types of gullies are formed when the erosive force of surface runoff surpasses the frictional resistance of the slope material (Harvey, 1992). Hillslope gullying is most frequently initiated as result of changes in the vegetation cover (Selby, 1993). Therefore, hillslope gullying may have been triggered at Mill Glen by the clearance of woodland which probably started to affect the Ochil hills shortly after 500 BC following the deforestation of the surrounding lowland areas (R. Tipping pers. comm 2008). Gully erosion may have also been exacerbated by the introduction of sheep farming to Mill Glen resulting in overgrazing and a reduction in vegetative cover. Such a mode for gully erosion induction has been interpreted for the Howgill Fells in northern England following the introduction of Scandinavian sheep farming practices in the 10th century AD (Harvey *et al*. 1981). The gullies at Mill Glen now have continuous vegetation cover and show no sign of widespread erosion. At the time of active gully incision, it is likely that debris flow activity was more prevalent at the site, with exposed material in gully walls and on the gully floor vulnerable to flow mass movement. Individual flows are considerably smaller in size at Mill Glen compared to the other study sites. This can be attributed to the fact that debris flow activity at the site is confined to the steeper lower slopes close to the Gannel Burn and thus the height of the slope subject to debris flow is smaller than at other study sites (figure 5.47).

The majority of debris flows observed in the field were triggered as shallow translational landslides in thin soils (0.3 - 0.6 m). Sampled debris flow source landslides mostly correspond with areas where there is a morphologically induced concentration of hillslope hydraulics. However, at the Pass of Drumochter the sampled source area occurred at the crest of the hillslope. At such locations, the hillslope material can be subject to tension which and consequential formation of tension cracks. These in turn promote infiltration of surface runoff into the slope material thus increasing the potential for a critical rise in pore water pressures (Nettleton *et al*. 2005). Soil profiles at the headscars of sampled source translational landslides indicated that at Glen Ogle 1, Glen Ogle 2, the Lairig Ghru and Drumochter the failure plane exists at depth in the superficial till or regolith cover just above the interface with underlying bedrock. The position of these slip planes is indicative of landslide initiation due to a rising phreatic surface and a gradual rise in pore water pressures resulting in deep seated failure (Brooks & Richards, 1994). At Mill Glen the failure plane was observed at a depth of 0.44 m from the surface within a soliflucted till horizon. Although the till layer was too hard to dig further down, it can be inferred that the slip plane occurs relatively close to underlying bedrock due to the presence of nearby rock outcrops. This suggests that failure at this location was also triggered by an increase in the height of the phreatic surface. Alternatively, at the source landslide of An Teallach 1, the failure plane was observed at a depth of 300 mm within an 800 mm thick mantle of niveo-aeolian sand deposits. The position of the failure plane close to the surface is indicative of failure in unsaturated soils where the downward migration of a wetting front results in loss of suction and failure at a shallow depth in the soil profile (Fourie, 1996; Springman *et al*. 2003; Wheeler *et al*. 2003). The position of the slip plane just below the root mat also suggests that the failure was facilitated at this depth due to the dissipation of mechanical support from roots. The failure plane at the sampled debris flow source areas on Glamaig and at An Teallach 2 were observed to exist at, or just above the interface between overlying regolith and relict talus. An exposed section through the talus down to the underlying bedrock in a gully wall observed on the granite side of Glamaig suggests that the thickness of the talus at the site is approximately 1 to 1.5 metres thick. At An Teallach, the talus sheet subject to debris flow has accumulated to an average height of 61 m under the rockwall (Ballantyne & Eckford, 1984) indicating much thicker talus deposits at this site. Therefore, it is inferred that shallow landsliding at these source areas was also triggered due to the downward migration of a wetting front rather than as a consequence of rising phreatic surface which would have more likely triggered deeper seated failures within the talus deposits (Brooks & Richards, 1994).

Geomorphological mapping has shown that the spatial distribution of debris flows at the study sites is strongly determined by the location of debris flow source landslides on the hillslope. The control of hillslope aspect and morphology on the route of downslope propagation and the location of debris deposition has also been demonstrated with flows following the steepest route downslope from the source area and forming debris lobes and fans where the gradient reduces towards the slope foot. In channelised debris flows the route taken by the mass movement is determined by the course of the stream channel. The route of debris flows can also be deflected by the presence of landforms such as debris cones (Drumochter), glacial moraines (An Teallach) (Ballantyne, 1981) and protalus ramparts (Lairig Ghru).

Observations made during this research have underlined the fact that debris flow activity can occur through mobilisation of exposed material in drift-cut gully floors and exposed talus. In such situations sediment availability exerts a critical control on the frequency and nature of the debris flow activity. At the Pass of Drumochter debris flows originating from gullies cut into thick accumulations of glacial drift have formed substantial debris cones. The steep walls of the gullies are prone to small scale slumping and slope wash. The psammitic schist bedrock at the study site also easily breaks down when exposed to weathering agents (Lukas, 2002). Thus, the gullies have a large and rapidly replenishable supply of mobilisable sediment for debris flow activity. This accounts for a high debris flow temporal frequency at the site with return periods reckoned to be approximately 10 to 15 years (Ballantyne, 2002a). Although to a lesser extent than at Drumochter, drift cut gullies up to 2 metres deep at the Lairig Ghru similarly provide a substantial supply of sediment for debris flow activity. The sampled debris flow at the Lairig Ghru propagates through such a drift-cut gully and terminates at an incipient debris cone containing approximately 1530 m^3 of material. At the Glamaig study site, large areas of exposed material provide a supply of mobilisable sediment which is sporadically reworked by debris flow activity. Thicker accumulations of debris flow deposits on the granite side of the mountain suggest a greater frequency of flow activity compared to the basalt side of the mountain. For example, a volume of approximately 731 m^3 was measured in the debris flow sampled on the granitic part of the mountain compared to 183 m^3 on the basaltic side (table 5.3).

At Glamaig the source area landslides occur on rectilinear slopes mantled by a thin, very organic soil. It is inferred that the slope at Glamaig was once covered by this organic soil layer before landsliding and erosion stripped the soil layer from many areas of the hillside, exposing the underlying talus slope which was then subject to frequent reworking by debris flow activity (figure 5.10). This suggests that the temporal distribution of debris flows at Glamaig may conform to the hypothesis that hillslope destabilisation in Scotland may have been initiated by extreme storms during the Little Ice Age and continued by less severe rainstorms to the present due to a lowered threshold for subsequent debris flow activity (Brazier & Ballantyne, 1989; Ballantyne & Harris, 1994). Radiocarbon dating and stratigraphic evidence in stacked debris flow deposits at Glamaig shows constant reworking of debris over the last 710 years (Curry, 2000a). Although this pre-dates the Little Ice Age it does suggest a reduced threshold over the last few centuries resulting in a debris flow temporal frequency sufficient to prevent formation of organic horizons over individual colluvial deposits. However, as this data relates to only one debris flow sink at the site, more extensive radiocarbon assay is needed at Glamaig to allow more accurate interpretations to be made on the timing of the commencement of widespread, continually active instability at the site.

Conversely, the effects of a limited supply of sediment on debris flow activity may be apparent at the An Teallach study site. Here debris flow deposits are visibly less volumous than at the Drumochter, Lairig Ghru and Glamaig study sites and the magnitudes of the two debris flows sampled in the field are smaller than those sampled from all other sites except Mill Glen (table 5.3). Although several debris flows were observed to have been initiated amongst frost shattered detritus on the upper slopes of the mountain, many of the source areas at An Teallach have a discontinuous mantle of niveo-aeolian sand deposits derived from deflation surfaces on adjacent plateaux (Ballantyne & Morrocco, 2006). Optically-stimulated luminescence dating of sand deposits indicate that erosion of the plateau surface was initiated between 1550 and 1700 AD, most probably as a consequence of vegetation degradation during a period of lengthy snow cover and exceptional storminess (Morrocco, 2005; Ballantyne & Morrocco, 2006). Consequently, the frequency and magnitude of debris flow activity at An Teallach may have been restricted by a limited sediment cover the extent of which was largely dependent on the supply of wind blown sand from adjacent plateaux to the north of Coire a Mhuillin. The plateau sand deposits and soils are now almost completely exhausted (Ballantyne & Morrocco, 2006). Thus sediment starvation on the hillslopes of the An Teallach study site due to the discontinuation of plateau to hillslope aeolian sediment transport may lead to a downturn in the temporal frequency of debris flow activity over the coming decades.

The sediment budget of two channelised debris flows investigated in detail at Glen Ogle indicate that the majority of the material deposited in the debris fans were sourced during channel propagation, where the flowing mass was augmented by gully wall failures and material entrained from the gully floor. This trend is typical for debris flows that are transported through stream channels (Hungr *et al*. 1984; Wieczorek *et al*. 2000; D'Agostino & Marchi, 2003). Accordingly, channelised debris flows can be described as accumulative events or *accumulative channelised debris flows*. The source landslides of both debris flows occurred on open hillslopes far from the slope foot before flowing into bedrock gullies and becoming hazardous accumulative debris flows which blocked the A85 trunk road. A similar transition from hillslope to channelised flow has occurred during other hazardous debris flow events in Scotland, such as at Invermoriston on the 13th/14th of August 1997 (Nettleton *et al*. 2005), Cairndow on the 9th of August 2004 (Winter *et al*. 2006), and near Rest and be Thankful on the A83 trunk road on the 28th of October 2007 (M. Winter pers. comm 2008). Thus, hillslope-gully coupling should be considered an important control on the development of hazardous channelised debris flows.

Due to the fact that the majority of material in channelised flows is entrained during gully transport, it follows that the characteristics of the channel heavily determine the magnitude of the flow event (Hungr *et al*. 1984; Fannin & Rollerson, 1993; D'Agostino & Marchi 2003; Sterling & Slaymaker, 2007). The magnitude of the Glen Ogle 1 debris flow was found to be greater than the Glen Ogle 2 debris flow both in terms of the volume of material and the size of particles involved. Compared to the gully debris track of the Glen Ogle 2 debris flow, the Glen Ogle 1 gully is longer and steeper (the Glen Ogle 1 gully is approximately 800 metres long with a mean gradient of 33° whereas the Glen Ogle 2 debris flow is 610 metres long and has a mean gradient of 25°) (Figure 5.36). The greater length of the Glen Ogle 1 gully provided a longer debris track and a greater potential for the entrainment of material from the channel floor or supplementation to the debris flow from gully wall failures. The steeper mean gradient of the Glen Ogle 1 gully also resulted in a greater potential velocity and therefore a more erosive flowing mass which had the ability to entrain more and larger debris and trigger a greater number of gully wall failures. Bedrock steps in the profile also resulted in localised, gradient induced increases in flow velocity and thus flow erosivity. The gully in which the Glen Ogle 1 debris flow was conveyed is also wider and deeper implying that the sediment capacity of the channel was greater than the comparatively shallower and narrower Glen Ogle 2 gully.

At all of the investigated debris flows a sample of the largest particles encountered on the terminal lobe were measured to give an indication of the maximum size of debris mobilised in each flow. The majority of sampled debris flow deposits had an average size of between 0.26 m and 0.42 m in diameter. However, the largest debris flow deposits at Mill Glen were much smaller than the other sites (0.03 to 0.2 m in diameter) whereas at Glen Ogle large particles up to 3m in diameter were encountered in the debris fan (table 5.5). The size of the largest debris in fans and lobes are determined by the size of particles present in the regolith subject to debris flow, in talus slopes and material in drift cut gullies subjected to reworking by flows, or the size of particles entrained from stream channels during channelised flow. The large particles deposited in the Glen Ogle 1 debris fan are a function of the high erosivity of the flowing mass due to the higher average gradient of the propagation gully and the greater volume of moving material allowing the entrainment of larger debris (see above). The sub-angular to very angular nature of the majority of the largest particles encountered on sampled debris flow terminal lobes and fans is a function of the local provenance of the deposits from regolith in the source area or from rock fall debris in talus reworked by the debris flows. The presence of sub-rounded particles in debris flow deposits at Glen Ogle can be attributed to the incorporation of material during gully propagation which had been subjected to rounding by fluvial erosion within the Glen Ogle 1 and 2 stream channels.

Evidence of earlier debris flow activity is sometimes apparent in the slope foot stratigraphy from the presence of buried colluvial deposits and organic palaeosols (Innes, 1983c; Brazier *et al*. 1988; Brazier & Ballantyne, 1989, Hinchcliffe, 1999; Curry 1999, 2000a, 2000b). Such a record was apparent in the stratigraphy of the Glen Ogle 1 debris fan in the form of stacked colluvial deposits from several debris flow events visible in the eroded bank of a channel running through the fan. Further evidence of earlier debris flow activity was apparent in the shape of uneven ground and large boulders in the immediate vicinity of the fresh August 2004 deposits which appear to be of a colluvial genesis. Although the age of the observed relict debris flow deposits have not yet been attained, the old military road that runs through the glen shows evidence of being effected by debris flow activity prior to the August 2004 event. The military road was constructed in 1749 (Taylor, 1976) therefore indicating a debris flow return period of less than 255 years.

Closer analysis of the geometric characteristics of the 9 debris flows measured in the field (figure 5.3) reveal linear relationships between certain data which provide further insight into some of the critical controls on the debris flow process discussed above. It is apparent from the data that the length of the debris flow has a strong influence on the nature of deposition with longer debris flows tending to be characterised by greater final volumes (figure 8.1) and lower deposit angles (figure 8.2). The relationship between debris flow length and final volume is strongly linear displaying a coefficient of correlation of 0.914. Longer debris flows provide greater opportunity for the entrainment of material particularly in the case of long channelised debris flows such as Glen Ogle 1 and 2 (see above) or hillslope flows which have incised drift cut gullies into the slope where there is a greater potential source of sediment from gully walls and channel floors (Lairig Ghru). Where greater volumes of material are entrained there is a greater potential for debris flows to reach lower angles at the slope foot under the effects of gravity thus increasing the run-out of debris flows. The fact that the deposition angle is often limited by the minimum slope foot gradient and is also strongly influenced strongly by the viscosity of the debris flow may account for the lower coefficient of correlation in figure 8.2.

It is also apparent from the data that there is a linear relationship between the source volume and the length of the sampled debris flows in which debris flows with larger initiating landslides tend to result in longer flows (figure 8.3). This can be explained by the fact that a greater initiating mass is more likely to gain the momentum to flow further downslope and attain velocities to enable higher erosivity and greater accumulation of material during propagation. However, it is clear that the propagation phase is more important for the determination of debris flow magnitude as demonstrated by a lower coefficient of correlation compared to the relationship between final volume and debris flow length.

The relationship between the slope angle at the source area of the sampled debris flows and the normalised spatial frequency of debris flows at each site is also linear in nature (figure 8.4). If the sampled source areas are assumed to be representative of the dominant upper slope angle at the sites this supports the assertion that sites with persistently steeper slopes such as Glamaig and the Lairig Ghru are more prone to debris flow activity.

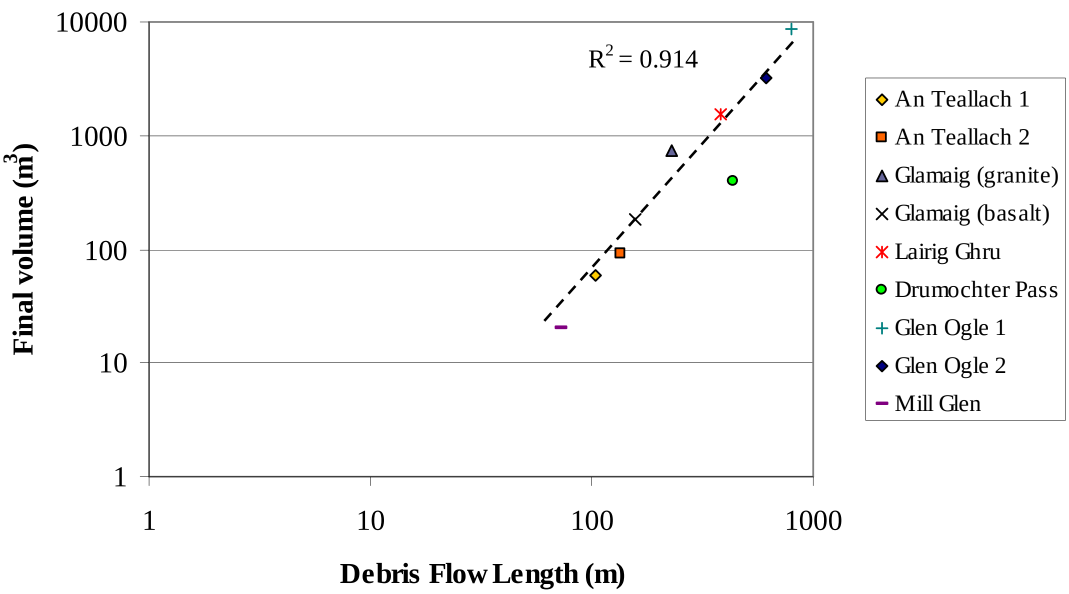


Figure 8.1: The final volume against the length of the 9 sampled debris flows.

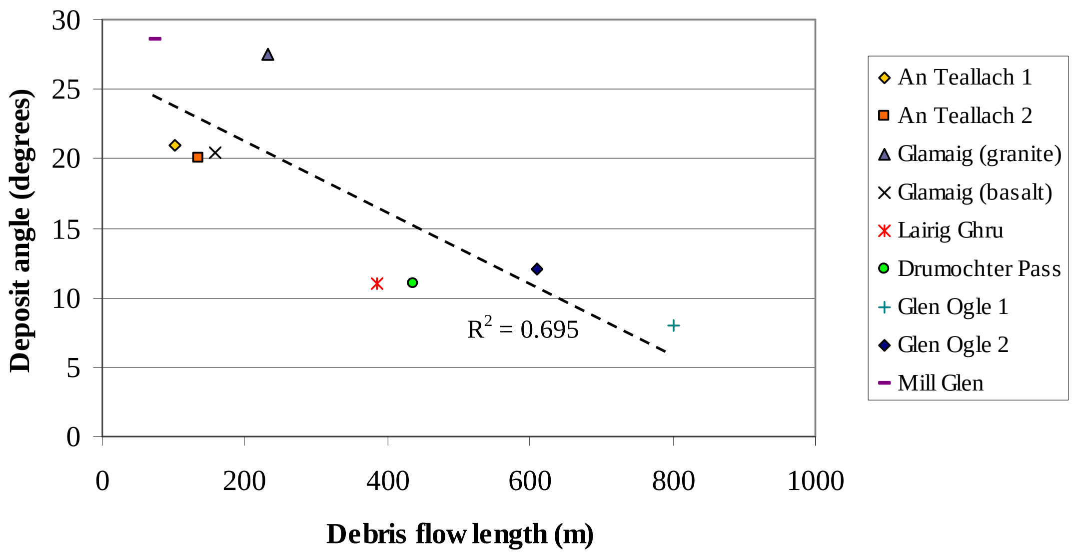


Figure 8.2: The slope foot deposition angle of the terminal debris lobe/fan plotted against the length of the 9 sampled debris flows.

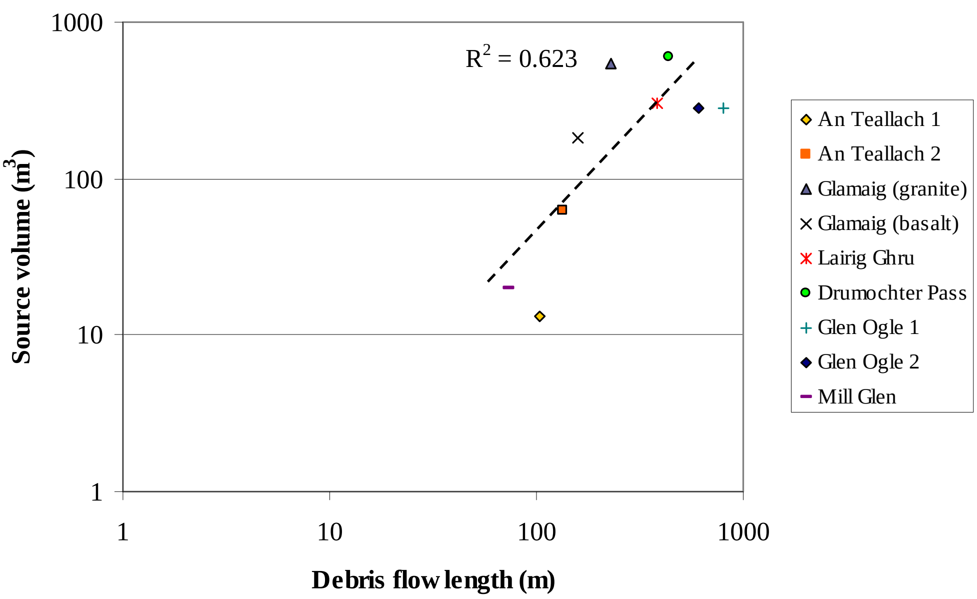


Figure 8.3: Gradient of sampled debris flow source areas against debris flow length.

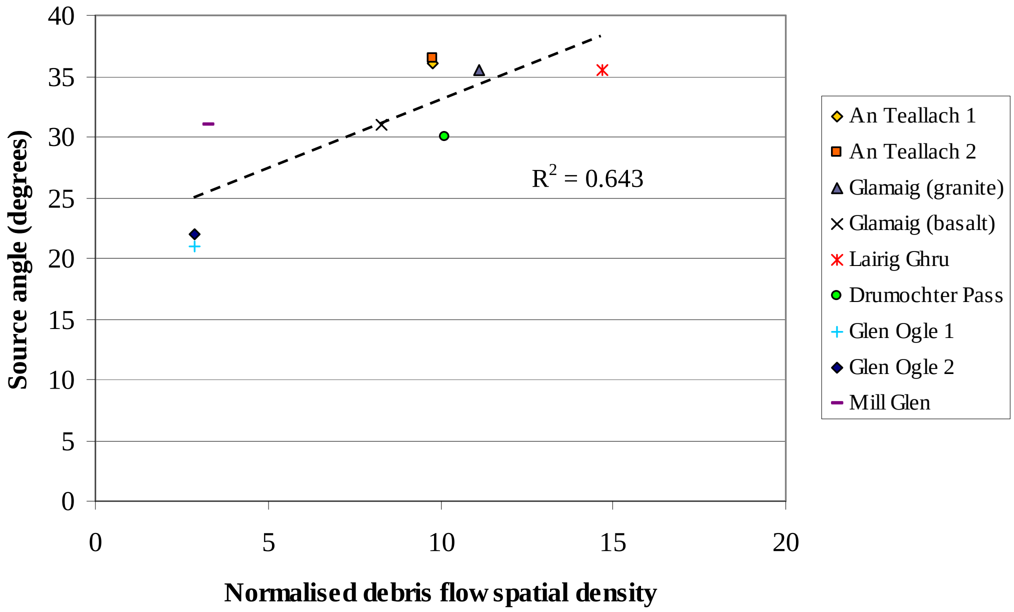


Figure 8.4: Gradient of sampled debris flow source areas against normalised debris flow spatial density.

8.2 Material Properties

The particle size distributions of the all sampled soil matrixes are characterised by a dominance of sand sized particles with samples collected from regoliths yielded from schistose and extrusive igneous bedrocks generally seen to display a greater component of silt sized particles than those developed over granite and Torridonian Sandstone (figure 6.1; figure 6.2; table 6.1). The dominance of sand sized particles in all the samples along with the prevalence of coarse silt particles in the silt fractions of all regolith specimens apart from Glamaig (granite) can be explained in terms of the preferential removal of smaller particles as a consequence of the flow of water through the regolith. This process is known as eluviation. Overland flow and splash erosion may also have contributed to eluviation although their influence is greatly reduced by vegetation cover (Innes, 1986). The proportion of clay sized particles was found to be negligible in all the tested specimens (figure 6.1; figure 6.2; table 6.1). This is unsurprising as Scottish upland environments are generally unfavourable for clay formation and any clay particles that are formed are vulnerable to removal by throughflow and leaching (Innes, 1986). It may be anticipated that a lower permeability in very organic soils may reduce the efficiency of eluviation resulting in higher clay and silt contents in such soils. However, in regoliths sampled in this research there is no visible trend indicating higher clay and silt contents in very organic soils. This suggests that high organic content is not sufficient to offset the effects of sediment impoverishment from throughflow.

The particle size distributions suggest a lithologically forced determination on soil type amongst the sampled regoliths with sandstone yielding *slightly silty sands*, granites and psammitic schists supporting *silty sands*, and *very silty sands* developing over mica schists and extrusive igneous lithologies. This pattern is determined by the properties of the parent material which in turn are dictated by the mode of genesis of the lithology. Mica schist and extrusive igneous rocks yield finer soils on weathering account of their genesis from siltstones and mudstones in the case of mica schist, and from rapid cooling of lavas resulting in the formation of small crystal sizes in the case of extrusive igneous lithologies. Conversely, granites are formed as plutons which slowly cool and solidify at depth in the Earth's crust resulting in the formation of larger crystals, and Torridonian Sandstone is a sedimentary rock formed from sands deposited in an ancient fluvial system (Gillen, 2003). Hence, granites and sandstone yield regoliths with a higher proportion of sand sized particles on weathering. The soil sampled at the Pass of Drumochter was found to have a coarser sediment texture than other specimens sampled over fine grained bedrocks. This is probably due to the fact that the psammitic schist bedrock at Drumochter is derived from sand dominated shallow marine deposits which disintegrate into coarser particles compared to other schistose lithologies.

The soil strength parameters determined from shear box tests show critical friction angles (φ'_{crit}) range between 29.1º for Drumochter to 47.5º for Mill Glen. The frictional strength is influenced by the number of point contacts in a volume of a soil, the arrangement, size, shape and resistance to crushing of grains. When packing of particles is open and particles are of uniform size, points of contact are relatively few and strength is low. Closer packing increases contact between grains as does a wide range of particle sizes and more angular grain shapes (Selby, 1993). The Mill Glen and Glamaig (granite) soils exhibited dilatancy during the shear tests indicating close initial packing of the tested samples. These soils exhibited peak friction angles (φ'_{max}) of 47.2º and 46.8º respectively. All the other soils generally experienced compression during the shear tests normally associated with loose initial packing of particles. The Glamaig (basalt), the Lairig Ghru and Drumochter soils were all found to have φ'_{crit} values close to 30º. The An Teallach 1 regolith has a φ'_{crit} of 38º. The higher value in the An Teallach 1 soil suggests closer packing of particles compared to the Glamaig (basalt), Lairig Ghru and the Drumochter samples. However, the friction angle is lower than that of the more loosely packed Glen Ogle 1 (42.7º) on account of the shape of the particles in the samples with the dominantly very angular and tabular particle shapes observed in the Glen Ogle regolith more likely to produce high friction angles than the sub-angular to sub-rounded and spherical particle shapes that comprise the An Teallach regolith (Cho *et al*. 2006). The φ'_{crit} measured from the Glamaig (granite) regolith (39.2º) is significantly higher than that measured in specimens from the basaltic part of Glamaig (32.1º). The higher φ'_{crit} in the Glamaig (granite) specimen is a result of closer packing as well as the very angular to angular shape of particles compared to the angular to sub angular particles in the basalt regolith. However, the presence of spherical shaped particles and the more poorly graded nature of the material ensured that the friction angle of the Glamaig (granite) regolith was lower than that encountered in the Glen Ogle 1 and Mill Glen samples. Similarly, the high friction angle at Mill Glen probably reflects a combination of close packing assisted by the well graded nature of the regolith and the presence of very angular particles. Higher apparent cohesion values (c') measured at Glamaig (granite) and Mill Glen are indicative of greater interlocking between particles compared to the other sampled soils due to the closer packing of the specimens. The high friction angles measured in the An Teallach 1, Glamaig (granite) and Glen Ogle 1 soils are similar to those in excess of 40º observed by Cho *et al* (2006) in poorly graded natural and crushed sands with very angular, low sphericity particle shapes. Fannin *et al* (2005) also report critical state friction angles of approximately 46-48º in coarse grained mountain soils from coastal British Columbia as measured in laboratory shear box tests on reconstituted specimens. Further analysis reveals that the relationship between the friction angle at sampled source areas and the normalised spatial frequency of debris flows at each site is linear (figure 8.5). Consequently, if the strength parameters at sampled source areas are typical of regolith mantling upper slopes at the study sites, the data underlines the importance of soil strength in determining hillslope susceptibility to debris flow activity.

When considering the shear strength parameters from debris flow source areas investigated in this research, it is important to acknowledge that debris flows are also mobilised in unconsolidated material on gully floors and exposed talus. It is likely that fine particles (smaller than 2mm in diameter) in talus and gully floor deposits are crucial for the generation of debris flow in this material as their presence is required to allow a sufficient rise in pore pressure to trigger flow mass movement (Salt & Ballantyne, 1997). However, talus and gully floor deposits are often clast dominated or have a high composition of clast sized particles (> 2mm). Therefore, interlocking between clasts is likely to have a strong influence on the strength of the material. Accordingly, to advance understanding of the process by which debris flows are triggered on gully floors and exposed talus, it would be beneficial to carry out large *in situ* shear box testing on these materials in order to allow investigation of the effect of in situ soil structure and the presence of clast sized particles on material strength (Springman *et al*. 2003; Fannin *et al*. 2005). More research is also required into the structure and geotechnical properties of talus slopes to allow more detailed inferences to be made on the mechanisms of debris flow generation in such material.

In constant head permeability tests the highest permeability coefficients (k) were measured in the Lairig Ghru and An Teallach samples with the lowest permeability measured in the Mill Glen specimen (table 6.4). The majority of the samples exhibit permeability coefficients compatible with those expected for coarse sands although the permeability of the Mill Glen sample is compatible with that expected for a fine sand

(Selby, 1993) (table 6.5). High organic contents tend to suppress the coefficient of permeability (Warburton *et al*. 2004). Consequently, the influence of particle size distribution on permeability can be interpreted through comparison of soils with similar organic contents. An Teallach 1, Lairig Ghru and Glen Ogle 1 have organic contents of 1%, 6.1 % and 1.7% respectively (table 6.3; figure 6.3). The permeability coefficient of An Teallach is approximately 6 times greater than the Glen Ogle soil with the Lairig Ghru in turn having a permeability 4 times greater than Glen Ogle. The Lairig Ghru, Glen Ogle and An Teallach samples are all loosely packed. However, stress displacement graphs in shear box tests on the An Teallach 1 regolith indicate a discrete peak in some tests suggesting that the packing of particles is closer in the An Teallach 1 specimen. This probably had the effect of slightly suppressing the coefficient of permeability. At Glamaig both sampled regoliths have a high organic content although the *very silty sand* at Glamaig (basalt) has a lower permeability coefficient than the *silty sand* regolith sampled at the granite side of the mountain. This suggests that the higher silt content has acted to contribute to the lower hydraulic transmissivity of the Glamaig (basalt) soil. The permeability of the Glamaig (granite) sample is also likely to have been curbed by denser packing of particles evident from the peak behaviour in stress displacement graphs in shear box tests. The regolith sampled at Drumochter also has a high organic content. However, the permeability is an order of magnitude higher than the sampled regoliths at Glamaig due to the loose packing of the Drumochter soil coupled with a relatively low silt content. At Mill Glen the lower permeability appears to be the result of the relatively high silt content, close packing of particles and an organic content of 14%. Thus, the results of the permeability tests demonstrate a general trend in which specimens with larger sand fractions tend to display a higher coefficient of permeability although the packing of particles and in particular the organic content also exert a strong influence on hydraulic transmissivity. Therefore, the results support the hypothesis expressed by Ballantyne (1986) that higher debris flow densities on slopes underlain by sandstone and granite lithologies are facilitated by the high permeability and rapid infiltration rates of overlying mountain sediments although it is apparent that the susceptibility of a hillslope to debris flow is likely to be further influenced by the effects of packing and organic content.

It is also important to acknowledge that in stratified soil profiles the presence of overlying soil horizons affect the ability of water to percolate into the regolith around a potential failure plane. For example, at Glen Ogle 1 the tested till layer within which the failure plane is located is overlain by a horizon of peat. Rycroft *et al*. (1975) presented data ranges for the permeability of peat ranging from 9×10^{-9} m s^{-1} for highly humified blanket peats to 5×10^{-4} m s^{-1} for slightly humified fen peats (Warburton *et al*. 2004). Due to the dense, humified nature of the peat horizon at Glen Ogle 1, it is likely that this peat would fall into the lower end of this range. Consequently, the infiltration of water into the till horizon at Glen Ogle would be have been retarded by this layer. At Drumochter, material was sampled from a well graded *organic silty sand* corresponding with the failure plane. This was overlain by a less well graded *organic silty sand* similar in texture and with a comparable *in situ* density to the matrix of the sampled horizon. At Mill Glen the sampled soliflucted till is overlain by a layer comprised of well graded Brown Forest Soil. The colour, texture and *in situ* densities of this horizon are also similar to the underlying layer indicating that the organic content, particle size distribution and packing of the Brown Forest Soil are analogous to the sampled till matrix. Consequently, it is assumed that the permeabilities of the upper layers at both Drumochter and Mill Glen are broadly similar to those of the tested horizons. It is also recognised that the permeability of talus and unconsolidated material in channel floors is important for the triggering of debris flows in such material. Consequently, further research is required into the permeability and behaviour of groundwater in such sediments.

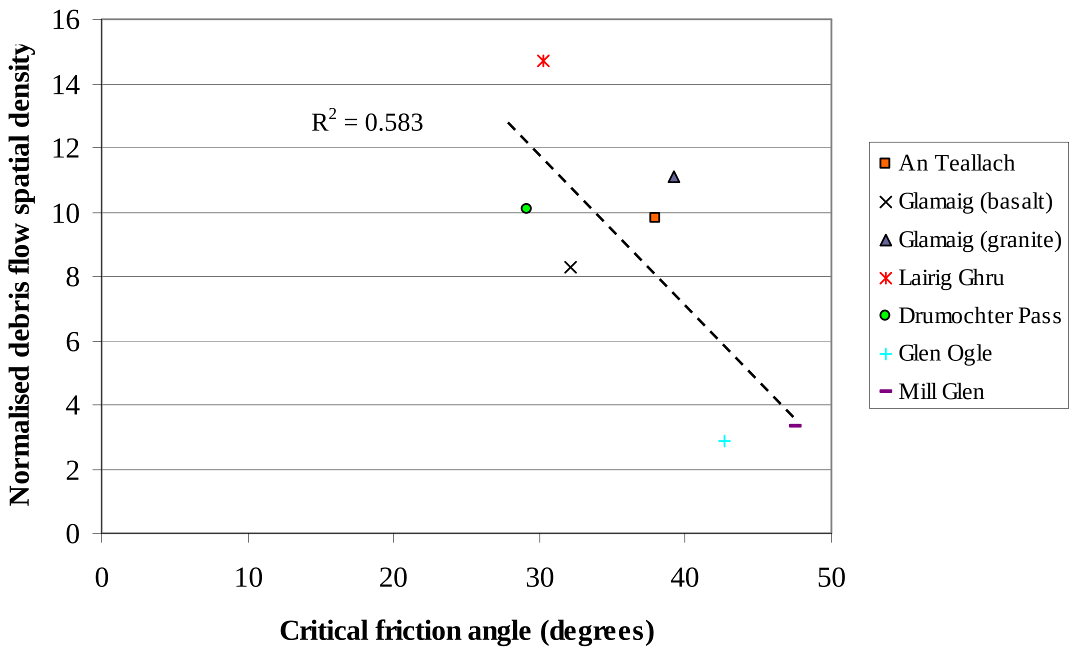


Figure 8.5: Critical friction angle of sampled debris flow source areas against normalised debris flow spatial density.

8.3 Source Area Stability Analysis

Using φ' and c' values determined from shear box tests and measured values for soil thickness above shear planes, slope gradients and *in situ* densities encountered in the field, it is possible carry out infinite slope analysis to investigate the impact of groundwater on slope stability at sampled debris flow source areas (appendix C). The values derived from infinite slope analysis are shown in table 8.1.

The Factor of Safety (Fs) when the slope is considered to be dry (h = 0) gives an indication of the maximum strength of the slope with a value reducing to one signifying greater instability (Summerfield, 1991). The Fs values show that the slopes at the source area at Glamaig (granite) and Glen Ogle 1 are the most stable. The relatively high Fs of 2.7 at Glen Ogle is a consequence of the high φ'_{crit} (table 6.6) coupled with the low slope angle at the source area (table 5.3). At Glamaig (granite) the slope gradient is greater but the safety factor is slightly higher (2.8) as a consequence of the relatively high apparent cohesion c' (table 6.6). Due to having a low slope angle and the highest φ'_{crit} value, the maximum Fs at Mill Glen (3) is higher than that at the other sampled source areas (table 5.3; table 5.4). The relatively low Fs at An Teallach 1 can be explained in terms of a very low apparent cohesion (0.1 kPa) and a steep gradient at the source area (36º). The Fs at the source area sampled at the Lairig Ghru was by far the lowest at 0.8. This indicates that this slope is intrinsically unstable even before a meteorological induced ingress of water. This reflects the fact that the φ'_{crit} (30.3º) is substantially lower than the source area gradient (35.5º) coupled with the absence of apparent cohesion. However, it is important to acknowledge that the friction angle measured in the shear box tests may underestimate the actual frictional strength of the *in situ* material due to an abundance of roots in the soil profile which will act to increase the frictional resistance at the source area (Buchan and Savigny, 1990; Fannin & Rollerson, 1993). Visual assessment of the profile also revealed the presence of a high quantity of gravel sized particles which were removed from the samples before being tested in the shear box. Although the profile appeared to be mostly matrix dominated it is possible that the presence of gravel may have exerted an influence on the friction angle due to localised interlocking between gravel sized particles. Therefore, it is likely that the calculated Fs at the Lairig Ghru underestimates the true factor safety. Nevertheless, it is clear that the source area appears to be more unstable than at the other study sites and the inherent weakness of the material may help to explain a higher debris flow density at the site.

The data also suggest that an increase in the phreatic surface to the top of the soil profile in the Glamaig (granite), Glen Ogle 1 and Mill Glen source areas is insufficient to cause failure, despite the fact that at each of these sites failure has occurred before. This may reflect a change in the structure of the soil as a result of the preparation of specimens from disturbed samples resulting in a higher φ'_{crit} value. Shear box tests also do not take into consideration weaknesses such as lenses and tension cracks that may have been present elsewhere in the source area. The calculated safety factors are applicable only to sampled source area failures. Therefore the safety factors do not take into consideration the stability of exposed talus at the sampled debris flows at Glamaig or material in the drift-cut gully at the sampled flow in the Lairig Ghru which are subject to reworking by debris flow. However, if the properties at sampled source areas are assumed to be broadly representative of wider conditions at each study site, the relatively low Fs encountered at the Drumochter, An Teallach and Lairig Ghru sampled source areas may help explain higher spatial frequency of debris flows at these study sites compared to Glen Ogle and Mill Glen.

Comparison of critical phreatic surfaces (the height of the water table when Fs is equal to one) for the centrifuge model soils (table 7.3) calculated from infinite slope analysis with the average height of the water table recorded immediately prior to slope failure during each centrifuge test (figure 7.17; table 7.6) gives an indication of the accuracy of the stability analysis. This reveals that the infinite slope analysis underestimates the critical phreatic surface by 13.4%, 8.7% and 14% for the *sand*, *silty sand* and *very silty sand* respectively, highlighting the conservative nature of the stability analysis.

Debris Flow	**Fs, u = 0**	**z** (m)	**hw** (m)**, Fs = 1**
An Teallach 1	1.1	0.3	0.06
Glamaig (basalt)	1.6	0.29	0.19
Glamaig (granite)	2.8	0.31	-
Lairig Ghru	0.8	0.42	0
Drumochter Pass	1.3	0.47	0.18
Glen Ogle 1	2.7	0.6	-
Mill Glen	3.0	0.44	-

Table 8.1: Safety factors (Fs) for the sampled source areas determined from infinite slope analysis and height of water in soil required to create instability (Fs = 1).

8.4 Centrifuge Modelling

The results of the centrifuge tests show than in model soil slopes with constant density, particle shape and material thickness, soils with higher proportions of silt can sustain a higher increase in pore water pressure and thus a greater reduction in effective stress before failure is induced (figure 7.14; figure 7.15; figure 7.16; table 7.5). Therefore, centrifuge modelling of hillslope debris flows have demonstrated that sandier soils are geotechnically more susceptible to slope failure associated with a rising phreatic surface. This can be attributed to the fact that more uniformly graded, sand rich soils have fewer inter-particle contact points resulting in a lower friction angle. Accordingly, the higher observed spatial frequency of debris flow on slopes with granite and sandstone bedrocks can be partially explained in terms of a lower critical pore pressure failure threshold amongst the sandier soil matrixes yielded from such lithologies.

The maximum flow rate of water required to incite a critical rise in pore pressure sufficient to trigger failure for each test varied considerably. The results show that the higher the sand content in the model soils, the greater the flow of water required to attain critical pore water pressures and trigger debris flow initiation. This trend is as a function of varying permeability in the model soils. In the coarsest soil, which comprised entirely of fine sand, high permeability results in the rapid transmission of water through the soil. Consequently, a higher rate of water ingress into the model is required to exceed drainage from the soil slope and induce an increase in the phreatic surface. In the *silty sand* and *very silty sand* soils, hydraulic transmissivity is lower due to smaller pore spaces.

Therefore, ingress of water into the model slope is able to exceed the volume draining from the slope at lower water flow rates.

In the centrifuge tests debris flow initiation was achieved by implementing a gradual upward increase in the phreatic surface via a reservoir tank rather than from a meteorologically induced downward infiltration of water as is the case in prototype situations. Nevertheless, the flow rates used in the centrifuge tests offer insights into the patterns of rainfall and types of rainstorms required to trigger debris flows in soils with varying particle size distributions. The lower rates of water required to elicit a critical rise in pore water pressures in the *silty sand* and *very silty sand* tests compared to the *sand* tests do not indicate that smaller magnitude rainstorms generate debris flow in finer material as in the field water influx into finer grained soils is impeded by lower infiltration rates. Conversely, the higher permeability and thus higher infiltration rates of sandier materials are conducive to rapid increases in pore water pressures during rainstorms where the magnitude of the meteorological influx of water into the soil exceeds the rate of pore pressure dissipation. The influence of antecedent rainfall on the soil moisture and phreatic surface before the onset of high magnitude rainfall is also a crucial control on the debris flow process (Church & Miles, 1987; Ballantyne, 2004a; Winter *et al*. 2005). Soil moisture is likely to dissipate more rapidly in soils with sandier matrixes due to their greater hydraulic transmissivity. Consequently, debris flows in the coarsest soils are more likely to be triggered by rainstorms which follow on immediately after high antecedent rainfall or by long duration frontal storms in which persistent rain will allow the water table to gradually rise. In such storms the majority of the rain tends to fall towards the end of the storm (Brooks and Richards, 1994) thus providing an upturn in infiltration which may trigger the critical increase in pore pressures required to initiate slope failure. Similarly, debris flows in the coarsest soils may also be initiated as a result of composite rainstorms where long duration frontal storms are punctuated by short duration high intensity convective rainstorms which trigger a sudden increase in infiltration. In soils with higher silt contents, high antecedent soil moisture conditions are more likely to endure for longer as a consequence of lower hydraulic transmissivity. Thus hillslopes mantled with *silty sand* to *very silty sand* soils will remain vulnerable to debris flow generation for a longer period following high antecedent rainfall. Examples of recently triggered debris flows may offer some evidence to support these interpretations. For example, at Dunkeld on the 9th of August 2004, debris flows which blocked the busy A9 trunk road were generated in sand rich glacio-fluvial deposits following prolonged heavy rainfall (Winter *et al*. 2006) whilst in 1956 numerous debris flows were triggered in the coarse regolith of the Cairngorms by a 3 day long frontal storm (Baird & Lewis, 1957). However, only one small debris flow was triggered at An Teallach during a storm in September 1981 in which over 140 mm of rain fell in 24 hours following a period of dry weather (Ballantyne, 2004a). Consequently, these events appear to conform with the inference that debris flows in material with coarse, sandier matrixes are more likely to be triggered by long duration storms rather than high intensity short duration events. Alternatively, debris flows triggered at Glen Ogle in August 2004 by a short duration, high intensity rainstorm a week after exceptionally high antecedent rainfall may signify the longer endurance of soil moisture in *very silty sands* compared to sandier regoliths.

In light of the varying flow rates required in the centrifuge tests coupled with the importance of antecedent rainfall, it can be inferred that the optimal particle size distributions for debris flow generation are *silty sands* which are permeable enough to allow a rapid infiltration of water but can also sustain high antecedent soil moisture conditions for longer. This may partially explain the trend in which the Lairig Ghru and Glamaig (granite) study sites, where the slopes are mantled by regoliths with *silty sand* matrixes, have higher debris flow spatial frequencies than at An Teallach where the regolith has a *slightly silty sand* matrix.

Tests carried out in this research have indicated that more centrifuge modelling is required in order to investigate the effects of infiltration on the rate of soil saturation. Consequently, it is recommended that further centrifuge modelling of hillslope debris flow initiation is carried out in a sealed environmental chamber in which varying intensities and durations of rainfall can be applied to the soil surface via atomising mist nozzles located above the model slope (Take, 2003; Hudacsek & Bransby, 2008). Scaling laws dictate that long periods of time can be modelled in the centrifuge and hot air can also be introduced into the chamber to simulate dry periods. Using this apparatus it is therefore possible to investigate the effects of varying patterns of antecedent rainfall and different lengths of time between the culmination of antecedent rainfall and the commencement of high magnitude, debris flow generating rainstorms on the vulnerability of a soil slope to failure. The effects of long duration, low intensity frontal rainstorms on pore pressure development in soil slopes could also be investigated. As well as the interaction between antecedent rainfall and rainstorms of varying magnitudes, model tests in an environmental chamber would also allow for the investigation of slope failure triggered during high intensity rainstorms as a result of a loss of suction at a shallow depth in the soil mantle caused by the ingress of a wetting front (Fourie, 1996; Springman *et al*. 2003; Wheeler *et al*. 2003) and in particular the antecedent and triggering conditions that contrive to generate these types of landslides.

The soils tested in the centrifuge were isotropic in nature. However, in the field soils are often anisotropic commonly with organic rich upper horizons overlying mineral soils such as was observed at the source areas of the Glen Ogle debris flows. The tests were also carried out on soils with a constant thickness, density and slope gradient and consequently the influences of varying density normal loads, densities and slope gradients on propensity to failure were not addressed in this research. Further centrifuge tests should also investigate the influence of anisotropy and varying densities, soil thicknesses and slope gradients on the susceptibility of different soils to debris flow.

8.5 Summary

Higher debris flow densities on slopes mantled by soils with coarser matrixes can be explained in terms of higher permeability and a greater geotechnical susceptibility to landslide failure evident from the results of the centrifuge tests although the susceptibility of a hillslope to debris flow is further influenced by the effects of packing and organic content. The spatial frequency of debris flow is also strongly influenced by slope geometry and morphology. Higher debris flow densities tend to occur at sites where the topography is characterised by persistently steep upper slopes, resulting in greater shear stresses, and a high incidence of potential debris flow source areas in the form of depressions, gullies and couloirs which facilitate a morphologically controlled, gravity induced concentration of hillslope runoff and subsurface drainage leading to soil saturation, reduced effective stress and instability. Sediment availability also exerts a critical control on the frequency and magnitude of debris flows. Debris flows investigated at Glen Ogle highlight that the majority of material in channelised debris flows is entrained during the gully propagation stage of the mass movement. The magnitude of channelised debris flows are heavily determined by the properties of the propagation gully in particular the length, gradient and sediment capacity. Hillslope-gully coupling has also been highlighted as a crucial control on the development of hazardous channelised debris flows. Different rates of water ingress into centrifuge model soils required to trigger a critical rise in pore pressures indicate that differing patterns of antecedent rainfall and rainstorms of varying synoptic origin are likely to trigger debris flow in different soil types. The centrifuge tests suggest that the optimal particle size distributions for debris flow generation may be *silty sands* which are permeable enough to allow a rapid infiltration of water but can also sustain high antecedent soil moisture conditions longer compared to *slightly silty sands*.

9. IMPLICATIONS FOR HAZARD MANAGEMENT

The findings from the field, laboratory and centrifuge investigations of topographic and material controls on the Scottish debris flow process are discussed in this chapter in terms of their implications for the management of the debris flow geohazard. This involves discussion of how the results may be used to inform assessment of the geohazard and how the results may assist the implementation of effective hazard mitigation. The suitability of possible approaches to hazard mitigation is also addressed.

9.1 Hazard Assessment

Accurate hazard assessment in order to identify areas where slope foot infrastructure is most likely to be affected by debris flow is crucial in order to allow effective management of the Scottish debris flow geohazard within budgetary constraints (Winter *et al*. 2005). The site specific degree of risk to slope foot infrastructure (hazard ranking) is the product of the likelihood of a debris flow occurring (hazard) and the impact and consequences the debris flow event may have (exposure) (Clayton, 2001; Winter *et al*. 2005). Calculated hazard rankings can be used in a Geographic Information System (GIS) to provide a multi-layered hazard map to identify areas of highest risk and allow for the prioritisation of resources for mitigative action (Huabin *et al*. 2005). This research has focused on the geometric and material contributions to the likelihood of debris flow occurrence on a given slope with implications for the level of hazard that should be assigned when calculating hazard rankings. These are discussed in this section in terms of material, topographic, geomorphological and stratigraphic indicators of hazard potency.

9.1.1 Hillslope material indicators

The spatial densities of debris flows measured at each study site indicate that hillslopes underlain by coarse grained lithologies, such as sandstone and granite, have a greater spatial frequency of debris flows than those underlain by finer grained mica schist or extrusive igneous lithologies (table 5.1; table 5.2; figure 5.1). This trend can be partially explained by the fact that coarse grained lithologies tend to yield sandier, more permeable regolith matrixes which allow a rapid increase in pore water pressures during high magnitude rainstorms (Ballantyne, 1986). Centrifuge tests on model soils of the same density but with varying particle size distributions have also shown that coarser soils are more susceptible to slope failure. Slope foot infrastructure in uplands mantled by soils with sandier matrixes is therefore more likely to be impacted by debris flow activity. Accordingly, bedrock type should be considered as a fundamentally crucial determinant on hazard ranking. Upland areas underlain by coarser grained lithologies such as granite and sandstone should be assigned a higher level of hazard compared to schistose rocks and extrusive lavas during hazard assessment.

9.1.2 Topographic indicators

Hillslope topography has been shown to exert a strong control on both the distribution and spatial frequency of debris flow. The majority of debris flows investigated in this study were initiated on open hillslopes slopes ranging between 30º and 36.5º although at Glen Ogle a combination of morphological and hydrological conditions allowed debris flow generation to occur on slopes with gradients of 21º and 22º. Elsewhere, debris flow initiation on slopes as low as 25.5º and 20º have been recorded (Innes, 1983b). Consequently, it is suggested that a lower limit of 20º should be applied for the identification of potential source areas during hazard assessment. This is significantly lower than the 26º suggested in the Scottish Road Network Landslide Study (Heald & Parsons, 2005). Although no debris flow initiation areas steeper than 36.5º were investigated in this research, previous research has encountered debris flows in Scotland initiated on slopes up to 46º (Ballantyne, 1981; Innes, 1983b). Based on these surveys, it has been suggested that it is unlikely that the maximum gradient for debris flow initiation on open hillslopes should exceed 45 - 50º (Heald & Parsons, 2005). This represents the upper limit at which a soil mantle with a sufficient thickness can accumulate (Innes, 1983b).

Debris flow source areas often correspond with features such as hillslope concavities, gully heads and in, or immediately downslope of rock couloirs and gullies amongst rocky crags where a morphologically controlled, gravity induced concentration of hillslope runoff and subsurface drainage promotes localised instability. Therefore, at sites where the hillslope profile is characterised by persistently steep upper slopes and a high incidence of potential source areas, there is a topographically driven propensity for frequent debris flow activity. Accordingly, higher assignments of hazard should be attributed to such sites. The spatial distribution of debris flows on a hillslope is determined by the location of source areas and the direction of debris flow propagation is controlled by the gradient and aspect of the slope with flow mass movement tending to follow the steepest gradients downslope. Therefore, higher localised levels of hazard should also be assigned to slope foot infrastructure located in potential debris flow run-out zones determined by the maximum gradient and aspect downslope of identified source areas. In this research debris flows were deposited on slopes as low as 8^{o}. Consequently, it is suggested that slope foot infrastructure on slopes as low as this in areas subject to debris flow are considered potentially at risk.

The distribution of stream channels is a crucial topographic control on the severity of the debris flow geohazard. Debris flows propagated through stream channels, particularly those within bedrock gullies, tend to entrain larger volumes of material and larger sized particles. Stream channels and gullies also provide a transport route from the source area to the slope foot where the debris can encroach on to the valley floor and impact on slope foot infrastructure. Consequently, *accumulative channelised debris flows* can be considered as the most hazardous type of debris flow and the highest hazard rankings should be attributed to locations where slope foot infrastructure intersects bedrock gullies and stream channels. At Glen Ogle and elsewhere in Scotland (Nettleton *et al*. 2005; Winter *et al*. 2006; M. Winter pers. comm 2008), source landslides occurred on open hillslopes far from slope foot infrastructure before flowing into bedrock gullies and becoming hazardous accumulative channelised debris flows. Consequently, hillslope-gully coupling should be recognised as a crucial control on the development of hazardous debris flows. Higher hazard rankings should be assigned to locations where potential source areas and bedrock gully stream channels exist in close proximity, and also where the geometry of the hillslope results in gullied stream channels having larger potential hillslope debris flow catchment areas thus increasing the likelihood of accumulative channelised debris flow occurrence.

The magnitude of channelised debris flows is strongly determined by the characteristics of the stream channel. The potential magnitude of channelised debris flows should be assessed through analysis of the morphology of gullies that interact with slope foot infrastructure with longer, steeper channels more likely to yield high hazard debris flows. The sediment capacity of the gullies can also be assessed through identification of mobilisable sediment sources such as from gully walls and debris dams (Hungr *et al*. 1984; D'Agostino & Marchi 2003). However, such an approach is labour intensive and should therefore only be utilised at very high hazard sites where hazard reduction measures are likely to be undertaken. More work is required to allow a generic categorisation of stream channels in terms of the anticipated magnitude of potential channelised debris flows determined by channel length, gradient and sediment capacity. Such a categorisation would be beneficial for the assignment of hazard rankings and would assist the prioritisation of sites for mitigation measures.

Despite the fact that channelised debris flows often deposit material within stream channels which can then supply sediment for subsequent events, it is important to recognise that debris flows tend to scour out mobilisable sediment thus reducing the overall sediment capacity of the channel. Consequently, before a debris flow of a similar magnitude can reoccur, recharge of stripped out parts of the channel must take place from slumping of sediment from the gully walls on to the channel floor, or by the weathering and disintegration of bedrock (Bovis & Jakob, 1999). Estimation of recharge rates is crucial for accurate assessment of the frequency and magnitude of future channelised debris flows. Estimated recharge rates are calculated by surveying stored sediment and then considering the period of elapsed time since the last debris flow to strip out the channel to give an indication of the rate of sediment placement (Jakob *et al*. 2005). Gullies cut through thicker deposits of glacial till or talus will be subject to greater recharge rates and channels in different bedrocks will experience varying rates of recharge. For example, channels formed in psammitic schist, which weathers rapidly when exposed to contemporary climatological conditions (Lukas, 2002), will experience a more rapid lithological recharge as a consequence of weathering. Extrusive igneous rocks are also more prone to chemical weathering compared to intrusive igneous rocks (Bowen, 1915), suggesting that channels formed in extrusive lithologies should produce a greater volume of sediment than channels with intrusive bedrocks (Sterling & Slaymaker, 2007). Further research is required to investigate and quantify differing recharge rates in gullies incised in various bedrocks and cut through varying thicknesses and types of drift and regolith for the purposes of hazard assessment.

9.1.3 Geomorphological indicators

Geomorphological evidence for previous debris flow activity is often sufficient to indicate an area of high hazard. For example, a hillslope exhibiting a high spatial frequency of landforms associated with debris flow activity can be considered to be more hazardous than one with a lower spatial frequency of debris flows. Furthermore, if the deposits at such a site are largely uncolonised by vegetation (indicating a relatively recent genesis), this could possibly indicate a higher level of hazard than a site where deposits are widely vegetated signifying a longer period of quiescence in debris flow activity. However, it is important to acknowledge that vegetation colonisation occurs at different rates in varying environments and materials.

Field observations have also shown that sediment supply is a strong determinant on the frequency and potency of debris flow. Sites with expanses of exposed talus are vulnerable to reworking by flow activity and debris flows which propagate through drift-cut gullies tend to have a ready supply of mobilisable sediment from gully floors and walls which can feed successive debris flows. Higher levels of hazard should be assigned to infrastructure in close proximity to such landforms. Accumulations of colluvial material at the slope can also act as an indicator of the severity of the debris flow geohazard. At the base of gullies subjected to frequent debris flow activity, large accumulations of colluvial deposits can form debris cones such as those that exist at the foot of the east facing slope of An Torc at the Drumochter Pass (figure 5.30). More subtle geomorphological evidence of previous debris flow activity from the Glen Ogle 1 gully was apparent in the sediment sink at the valley bottom in the shape of uneven vegetated ground and large boulders which appear to be of a colluvial genesis in the immediate vicinity of the fresher August 2004 debris. The distribution of debris flow deposits from previous mass movement events can also be used to indicate the level of risk to slope foot infrastructure. For example, on the east side of the Drumochter Pass, the busy A9 trunk road runs approximately 100 m away from the foot of the slope. Although there has been debris flow activity on this slope, geomorphic evidence suggests that all previous flows have terminated a safe distance away from the location of the road. As the magnitude of preceding debris flows has been insufficient to reach the road, it can be inferred that future flow activity on this slope is unlikely to be much greater in scale and that debris flow activity presents only a low level risk to the road.

9.1.4 Stratigraphic and Archaeological Indicators

As demonstrated in the debris sink at Glen Ogle 1, evidence of earlier debris flow activity is often apparent in the stratigraphy of slope foot deposits. The number of discernable stacked debris flow deposits in the slope foot stratigraphy may act as an indicator of the susceptibility of a given hillslope to debris flow activity. The thickness of individual deposits may also act as an indicator of the magnitude of previous events and allow inferences to be made on the potential scale of future debris flows at the site. Radiocarbon dating of buried organic soils between colluvial deposits has been used to attain maximum and minimum ages for fossilised debris flow deposits at several locations in the Scottish Highlands (Innes, 1983; Brazier *et al*. 1988; Brazier & Ballantyne, 1989; Hinchliffe, 1999; Curry, 2000a, 2000b; Reid & Thomas 2006). Sampling of palaeosols for radiocarbon dating may allow for inferences to be made about the site specific temporal frequency of debris flow activity through the calculation of recurrence intervals. If a site was found to have a relatively low debris flow return period this would indicate a higher level of hazard. Establishing debris flow recurrence intervals under past climatic conditions may also allow for more accurate inferences to be made about the effect anticipated climatic change may have on the temporal frequency of debris flow activity. However, it is important to acknowledge that ^{14}C dating of debris flow deposits is prone to error particularly as a consequence of sample contamination by younger carbon (Lowe & Walker, 1997). Calculation of debris flow temporal frequency from radiocarbon assay is also dependent on finding intervening palaeosols lain down during periods of quiescence after debris flow deposition. High temporal frequency or subsequent erosion may have prevented the formation or removed datable organic soil thus preventing accurate calculation of return periods.

Datable structures can also serve as archaeological markers for previous debris flow activity. For example, at Glen Ogle a military road constructed in 1749 showed evidence of being affected by a debris flow from the Glen Ogle 1 stream channel prior to the 18th of August 2004 event, suggesting a debris flow recurrence interval of less than 255 years. Elsewhere, J.L. Innes reportedly observed evidence of a recent upturn in debris flow activity in the shape of abandoned field systems which had been buried by debris flow deposits (Ballantyne, 2004a).

9.2 Mitigation

At locations where it is found that there is a high susceptibility to debris flow activity in conjunction with a high level of exposure to slope foot infrastructure, it is necessary to carry out mitigative action to reduce the potency of the geohazard. Mitigation may take the form of exposure reduction, in which steps are taken to decrease the number of vulnerable infrastructure users during a period of heightened hazard or hazard reduction, in which physical measures are applied to protect infrastructure from debris flows. In this section options for mitigating the Scottish debris flow geohazard are discussed with reference to the findings made in this research. Comments are also made on the suitability of the possible approaches to mitigating the debris flow geohazard in Scotland.

9.2.1 Debris flow forecast and exposure reduction

Exposure reduction may be achieved through the establishment of a debris flow warning system based on rainfall monitoring in areas with a propensity to debris flow (Sloan *et al*. 2005). In order to accomplish this, it would be necessary to accurately monitor antecedent rainfall using a network of automatic rain gauges to allow interpretations to be made on soil moisture conditions. This coupled with weather forecast of high magnitude rainstorms could allow recognition of the combination of meteorological conditions that lead to a higher likelihood of debris flow initiation. A similar predictive system is successfully operated in Hong Kong (Sloan *et al*. 2005). Following identification of meteorological precursors to high debris flow likelihood, exposure to the geohazard would be reduced by informing infrastructure users through public announcements of heightened potential for slope failure in certain locations or by temporarily closing a stretch of road or railway that was thought to be at particularly high transient risk of impact from debris flow. Such exposure reduction methods are likely to result in occasional false alarms and there is also the potential of slope failure out with periods of anticipated heightened hazard. Furthermore, closure of roads during periods of perceived high risk will have socio-economic impacts associated with disruption to local, tourist and freight traffic. It may also take several years of observation following the establishment of such a system before operators can accurately interpret threshold values of antecedent rainfall that most likely lead to initiation (Sloan *et al*. 2005).

The results of centrifuge modelling of hillslope debris flow initiation carried out during this research have implications for the prediction of debris flows in soils yielded from different rock types. Water ingress rates initiating failure in the centrifuge model tests suggest that debris flows in soils with constant density and depth but varying particle size distributions are likely to be triggered by different patterns of rainfall due to variance in hydraulic transmissivity. Debris flows in the coarsest regoliths (i.e.: *slightly silty sands* to *silty sands*) such as those yielded from sandstone and coarse granites, are more likely to be triggered by rainstorms which follow on immediately after high antecedent rainfall or by long duration frontal storms in which persistent rain invokes a gradual rise in the phreatic surface to a critical height in the soil mantle. In finer grained regoliths, antecedent soil moisture conditions are likely to endure for longer as a consequence of lower hydraulic transmissivity so that hillslopes mantled with *silty sand* to *very silty sand* soils (such as those commonly developed over schistose and extrusive igneous parent materials) will remain vulnerable to debris flow generation for a longer period subsequent to antecedent rainfall. In such soils, debris flows may be triggered by both convective and frontal rainstorms following a period of high antecedent rainfall although lower infiltration rates caused by higher silt sized fractions inhibits landslide initiation.

Further centrifuge tests in an environmental chamber are necessary to investigate the effects of antecedent rainfall on debris flow activity in soils with different particle size distributions for the purposes of determining the temporal patterns and magnitudes of antecedent rainfall that result in optimal conditions for debris flow generation. Such tests should also examine the effects of simulated rainstorms of different synoptic origin on slope stability in soils with varying particle size compositions. A data set from a programme of physical modelling in a centrifuge environmental chamber has direct applicability in assisting prediction of rain induced debris flow activity as it may provide threshold levels associated with endurance of soil moisture and infiltration rates in soils with varying coarsenesses. These could then be used along with generalised or measured stability parameters (frictional strength, apparent cohesion, density and mantle thickness above probable failure plane) to carry out GIS based probabilistic forecasting of debris flow generation using two dimensional infinite slope analysis, likely antecedent moisture conditions (extrapolated from measured rainfall and the hydraulic transmissivity of the soil) and likely infiltration during forecast storms (Huabin *et al*. 2005; Schmidt *et al*. 2008).

9.2.2 Hazard reduction measures

At sites where a very high propensity to debris flow corresponds with frequently used slope foot infrastructure, it may be necessary to reduce the geohazard potency through the use of engineering works. Such engineering solutions are most likely to be applied at gullies and stream channels due to the fact that they transmit the most hazardous accumulative channelised debris flows.

A possible approach to reduce the debris flow hazard around stream channels and gullies is to arrest the progress of flows before they reach the road. This can be done through the construction of a debris retention basin or installation of a flexible ring net barrier system. Debris retention basins control debris flow by acting as a dam so that coarse grained debris are contained within the basin whilst water and fine grained sediment can escape through a straining outlet structure (VanDine, 1996) (figure 9.1). Debris retention basins are usually used to mitigate larger debris flows than those experienced in Scotland. For example, in British Columbia basins with design flows of up to 75,000 m^3 have been constructed (Couture & VanDine, 2004). Flexible barriers absorb the kinetic energy of the flow allowing drainage of water from the trapped debris through the high permeability barrier. This acts to reduce the efficiency of the debris flow, creating a dam of solid material strong enough to retain the remainder of the mass movement (Wendeler *et al*. 2006). Individual flexible ring net barriers are able to accommodate debris flows with volumes up to 5000 m^3 although multiple barrier systems can mitigate much larger events (figure 9.2). It is important to acknowledge that debris retention basins and barrier systems are high maintenance options, requiring removal of trapped material subsequent to debris flow. Such measures also can have a considerable aesthetic impact on the landscape, particularly in the case of retention basins.

Where high hazard stream channels or gullies interact with the road or rail network, increasing the capacity of culverts to accommodate debris flows would mitigate the hazard by ensuring flows passed harmlessly under the road or railway. Such an approach would have lessened the impact of the 18th of August 2004 event at Glen Ogle where hazardous debris flows followed the course of stream channels down to the road, whereupon culverts were rapidly blocked with debris leading to the spillage of material over the road surface (Winter *et al*. 2006). In such circumstances it may also be beneficial to improve channel flow down to and beyond slope foot infrastructure to allow the rapid direction of debris flows away from elements at risk (Sloan *et al*. 2005). Such an approach was applied at MacKay creek in British Columbia by lining the walls and floor of the creek with shortcrete (Couture & VanDine, 2004) (figure 9.3). Although taking this measure at Glen Ogle or elsewhere in Scotland would have a detrimental visual impact, more aesthetically sensitive approaches could be taken to improve channel flow such as straightening and widening the lower reaches of gullies. At Glen Ogle 1 the position of a dog leg in the channel immediately upslope of the road also accentuated the severity of the geohazard as a result of a high magnitude debris flow pulse passing over the apex of the bend and impacting on a larger section of the road. Accordingly, during the planning of future transport infrastructure, culverts with a larger than necessary capacity to accommodate flowing debris should be aligned straight on to stream channels avoiding proximal gully bends.

At locations where there is a significant hazard it may be possible to protect short stretches of roads and railway lines using debris flow shelters. Such a structure is in use to the northeast of Stromeferry in the northwest Highlands where it protects the A890 trunk road and the adjacent railway line (Sloan *et al*. 2005) (figure 9.4).

In extreme situations where there is an exceptionally high debris flow geohazard coupled with high exposure, it may be necessary to consider realigning roads or railways away from slopes with high susceptibility to debris flows. Such an approach has been used in the past on the Scottish railway network at Stromeferry, Penmansheil and Dolphinston where the severity of the mass movement geohazard were considered severe enough to justify the high cost of realignment (Sloan *et al*. 2005). At locations where the avoidance of high debris flow hazard is not possible, planners should position or realign roads and railways away from the lower reaches of potential run-out zones where deposition of debris fans may potentially impact a larger area of the road. In such cases it is more favourable for infrastructure to be positioned straight on to gullies (as described above) where debris flows may be allowed to pass under the road in high capacity culverts.

Due to the high costs of hazard reduction engineering measures, they can only be considered for installation at locations where the geohazard potency is greatest (Sloan *et al*. 2005). As well as the high financial costs associated with construction and maintenance, it is also very important to acknowledge the environmental impacts hazard reduction approaches may encompass, in particular the detrimental aesthetic impact some engineering options would have. Consequently, it is recommended that hazard management in Scotland is strongly geared towards the utilisation of lower impact approaches revolving around exposure reduction and, as much as is safely possible, less visually intrusive engineering approaches at high hazard areas such as increasing culvert size. Where other hazard reduction mitigation techniques are necessary, effort should be made to reduce the visual impact as much as possible.

Figure 9.1: View from within a debris retention basin (design capacity 33,000 m^3) at Charles Creek, British Columbia, Canada.

Figure 9.2: One of the 13 flexible ring net fences in the debris flow and avalanche barrier system at Hasliberg, Berner Oberland, Switzerland. The retaining volume of the system is 10,000 m^3 (Geobrugg, 2007).

Figure 9.3: Engineered stream channel debris flow mitigation approach at Alberta Creek, Highway 99, British Columbia, Canada.

Figure 9.4: Shelter protecting the A890 and the adjacent railway northeast of Stromeferry in the northwest Highlands (Source: Sloan *et al*. 2005).

9.3 Summary

This research has indicated that the highest hazard rankings should be assigned to slope foot infrastructure in proximity to stream channels in bedrock gullies with high sediment capacities and long, steep profiles conducive to large accumulative channelised debris flows. Other hillslope characteristics that may signify elevated hazard potency include:

- Sandier regolith mantles
- Large channelised debris flow catchment areas
- Persistently steep upper slopes
- High spatial frequency of potential debris flow source areas
- High spatial density of existing debris flows
- Large accumulations of colluvial deposits at the slope foot (debris fans, debris cones).

During site specific hazard assessment, the distribution of debris flow deposits from previous mass movement events can be used to indicate the level of risk to slope foot infrastructure. Radiocarbon dating of relict debris flow deposits in sediment sinks at the bottom of gullies may allow for the calculation of debris flow return periods although it is important to acknowledge that this approach is prone to error. Archaeological markers such as military roads or other historic infrastructure may sometimes assist determination of recurrence intervals.

Due to the importance of gullies in determining the severity of the debris flow geohazard, it is suggested that hazard management practices are focused around bedrock gullies. To avoid detrimental aesthetic impact associated with many hazard reduction approaches, it is recommended that hazard management is strongly geared towards the utilisation of lower impact approaches revolving around exposure reduction and less visually intrusive engineering approaches such as increasing culvert capacity to accommodate debris flows. Where other hazard reduction approaches are deemed necessary, effort should be made to reduce the visual impact as much as possible. During realignment or the planning of future transport infrastructure, culverts with capacities significantly exceeding those required for purely hydrodynamic considerations should be placed straight on to stream channels avoiding proximal gully bends.

10. Conclusions and Recommendations

Debris flows can be considered the most significant geological hazard in areas of high relief in Scotland. The potency of this geohazard is anticipated to increase over the coming decades due to a climatologically enforced upturn in debris flow frequency. Consequently, it is important that we understand as much as possible about the controls on debris flow activity to allow optimal conceptualisation and management of the debris flow geohazard. This research has investigated material and topographic controls on Scottish debris flow activity using a combination of field and laboratory based analysis of debris flows at six study sites. Centrifuge modelling has also been used to simulate the initiation of debris flows in soils with varying particle size distributions. The conclusions and recommendations derived from this study are summarised in the following sections.

10.1 Material controls

In agreement with previous research (Ballantyne 1986; Innes, 1983b; Curry, 1998, 2000a), spatial densities of debris flow measured in the field indicate that hillslopes underlain by sandstone and granitic bedrocks, which tend to be mantled by coarser sand rich soils, have a greater frequency of flows than those underlain by schist and extrusive lava bedrocks. This trend largely persists following normalisation with site specific average annual rainfall totals despite the fact that the study site locations underlain by granite and sandstone have higher average annual rainfall totals and are therefore meteorologically more predisposed to debris flow activity. Although all the sampled regoliths are dominated by sand sized particles, particle size analysis suggests a lithologically forced determination on soil type amongst the sampled regolith matrixes with sandstone yielding *slightly silty sands*, granites and psammitic schists supporting *silty sands*, and *very silty sands* developing over mica schists and extrusive igneous lithologies (BSI, 1981). This pattern is determined by the properties of the parent material which in turn are dictated by the mode of genesis of the lithology. Permeability tests demonstrated a general trend in which specimens with larger sand fractions tended to display higher permeability coefficients therefore supporting the hypothesis of Ballantyne (1986) that higher debris flow densities on slopes underlain by sandstone and granite lithologies are facilitated by the high permeability and rapid infiltration rates of overlying sandier mountain sediments thus allowing a more rapid increase in pore water pressures during rainstorms. However, it is also apparent that the susceptibility of a hillslope to debris flow is likely to be further influenced by the effects of packing and organic content with denser packing and higher organic content acting to suppress permeability. Infiltration is also impeded in stratified soils by organic rich upper horizons.

Amongst natural sampled soils a large variance in effective strength parameters was observed due to the variability of the determining soil characteristics of particle packing, shape and size. However, centrifuge tests carried out on model soil slopes with constant density, particle shape and material thickness, show that soils with higher proportions of silt can sustain a higher increase in pore water pressure and thus a greater reduction in effective stress before failure is induced. Thus, centrifuge modelling of hillslope debris flows in this study has demonstrated that sandier soils are generally geotechnically more susceptible to slope failure due to the fact that more uniformly graded, sand rich soils have fewer inter-particle contact points resulting in a lower friction angle. Therefore, the higher observed spatial frequency of debris flow on slopes with granite and sandstone bedrocks can be partially explained in terms of lower critical pore pressure failure thresholds amongst the sandier soil matrixes yielded from such lithologies.

Different rates of water ingress into centrifuge model soils required to trigger a critical rise in pore pressures suggest that differing patterns of antecedent rainfall and rainstorms of varying synoptic origin are likely to trigger debris flows in different soil types. The higher permeability and thus higher infiltration rates of sandier materials are conducive to rapid increases in pore water pressures during rainstorms where the magnitude of the meteorological influx of water into the soil exceeds the rate of pore pressure dissipation. However, high antecedent soil moisture conditions which are normally a prerequisite to debris flow generation are liable to dissipate more rapidly in soils with sandier matrixes due to their greater hydraulic transmissivity. Consequently, debris flows in the coarsest soils are more likely to be triggered by rainstorms which follow on immediately after high antecedent rainfall, by composite storms or by long duration frontal storms in which persistent rain will allow the water table to gradually rise (Brooks & Richards, 1994). Conversely, in soils with higher silt contents, high antecedent soil moisture conditions will persist for longer as a consequence of lower hydraulic transmissivity meaning that hillslopes mantled with *silty sand* to *very silty sand* soils will remain vulnerable to debris flow generation for a longer period subsequent to high antecedent rainfall. In light of the varying flow rates required in the centrifuge tests coupled with the importance of antecedent rainfall, it may be inferred that the optimal particle size distributions for debris flow generation are *silty sands* as these are permeable enough to allow a rapid infiltration of water but can also sustain high antecedent soil moisture conditions for longer. This may partially explain higher observed debris flow densities at the Lairig Ghru and Glamaig (granite) study sites, where the slopes are mantled by regoliths with *silty sand* matrixes, compared to the An Teallach study site where the regolith has a *slightly silty sand* matrix.

10.2 Topographic controls

Observations in this research have underlined the fact that the susceptibility of a hillslope to debris flow is strongly influenced by slope geometry and morphology as well as by material controls such as particle size distribution and permeability. Higher debris flow spatial densities tend to occur at sites where the topography is characterised by rectilinear or concave slope profiles with persistently steep upper slopes and a high incidence of potential debris flow source areas in the form of depressions, gullies and couloirs often amongst rocky crags. At such locations steep upper slopes result in greater shear stresses and thus greater instability whilst depressions, gullies and couloirs can facilitate morphologically controlled, gravity induced concentrations of hillslope runoff and subsurface drainage which can lead to soil saturation, reduced effective stress and instability. Consequently, hillslopes with persistently steep slopes and a high incidence of concavities, gullies and couloirs are topographically more predisposed to debris flow activity.

Mapping of debris flows has shown that the spatial distribution of debris flows at the study sites is strongly determined by the location of debris flow source landslides on the hillslope. The control of hillslope aspect and morphology on the route of downslope propagation and the location of debris deposition has also been demonstrated with flows following the steepest route downslope from the source area and forming debris lobes and fans where the gradient reduces towards the slope foot. In channelised debris flows the route taken by the mass movement is determined by the course of the stream channel.

Sediment availability is highlighted as an important determinant on the frequency and nature of the debris flow activity. Hillslope debris flows which have formed drift cut gullies tend to be larger in scale often terminating in incipient or fully formed debris cones such as at the Lairig Ghru and Drumochter Pass study sites respectively. Exposed material in talus slopes is also susceptible to reworking by debris flow activity. Debris flows generated in Glen Ogle on the 18th of August 2004 demonstrate that the majority of material in channelised debris flows is entrained during the gully propagation stage of the mass movement. Consequently, such events can be considered *accumulative channelised debris flows*. Longer and steeper gullies with greater sediment capacities are more likely to yield larger flow mass movements. Coupling between open hillslopes and bedrock gullies has also been shown to be an essential component for conceptualisation of the debris flow geohazard with the generation and spatial distribution of hillslope flows strongly influenced by topographical controls on hillslope hydrology.

10.3 Recommendations for hazard management

Due to the role they play in amplifying debris flow magnitude, hazard management should be focussed around bedrock gullies and stream channels. It is suggested that the highest hazard rankings should be assigned to slope foot infrastructure in proximity to gullied stream channels with high sediment capacities and long, steep profiles conducive to large accumulative channelised debris flows. Other hillslope characteristics that may signify elevated hazard potency include:

- Sandier regolith mantles
- Large channelised debris flow catchment areas
- Persistently steep upper slopes
- High spatial frequency of potential debris flow source areas
- High spatial density of existing debris flows
- Large accumulations of colluvial deposits at the slope foot (debris fans, debris cones).

During site specific hazard assessment, the distribution of debris flow deposits from previous mass movement events can be used to indicate the level of risk to slope foot infrastructure. Radiocarbon dating of relict debris flow deposits in sediment sinks at the bottom of gullies may allow for the calculation of debris flow return periods although it is important to acknowledge that this approach is prone to error. Archaeological markers such as military roads or other historic infrastructure may sometimes assist determination of recurrence intervals.

To avoid detrimental aesthetic impact associated with many hazard reduction approaches, it is recommended that hazard management is strongly geared towards the utilisation of lower impact approaches revolving around exposure reduction and less visually intrusive engineering approaches such as increasing culvert capacity to accommodate debris flows. Where other hazard reduction approaches are deemed necessary, effort should be made to reduce the visual impact as much as possible. During realignment or the planning of future transport infrastructure, culverts with capacities significantly exceeding those required for purely hydrodynamic considerations should be placed straight on to stream channels avoiding proximal gully bends.

10.4 Recommendations for future work

This research has highlighted several areas where further work is required to advance understanding of the debris flow geohazard. As a result of the importance of bedrock gullies and stream channels in determining the severity of the debris flow geohazard, it is suggested that further research is carried out with a view to developing a generic categorisation of stream channels in terms of the anticipated magnitude of potential channelised debris flows to allow assignment of more accurate hazard rankings and assist the prioritisation of sites for mitigation measures. It is anticipated that such a categorisation could apply the general principle outlined in the conclusions of this research that longer, deeper, steeper and wider channels are more likely to yield larger debris flows to identify high hazard locations. Subsequently, channels interpreted as presenting a high level debris flow hazard should undergo a detailed survey to allow quantification of gully sediment capacity to inform the selection and application of mitigative approaches (Hungr *et al*. 1984; D'Agostino & Marchi 2003). It would also be beneficial to compile a database of debris flow events associated with Scottish slope foot infrastructure to help identify areas of high hazard. The value of such a database would be optimised if records of historical debris flows and geomorphological, stratigraphic and archaeological evidence of past activity was included.

In this research shear strength parameters from debris flow source areas were investigated. However, field observations have highlighted that debris flows are often mobilised in unconsolidated material on gully floors and exposed talus. It is likely that the presence of particles smaller than 2mm are crucial for the generation of debris flow in talus and gully floor deposits as their presence is required to allow a sufficient rise in pore pressure to trigger flow mass movement (Salt & Ballantyne, 1997). However, these materials are largely clast dominated or have a high composition of clast sized particles (> 2mm). Therefore, interlocking between clasts is likely to have a strong influence on the strength of the material. A programme of large *in situ* shear box testing on these materials to allow investigation of the effect of *in situ* soil structure and the presence of clast sized particles on material strength would help advance understanding of the process by which debris flows are triggered in gully floors and exposed talus thus assisting conceptualisation of the debris flow geohazard associated with talus and gully floors (Springman *et al*. 2003; Fannin *et al*. 2005). More generally, further research is required into the structure and geotechnical properties (e.g. hydraulic transmisivity, stratification, particle size distribution) of talus slopes to allow more detailed inferences to be made on the mechanisms of debris flow generation in such material.

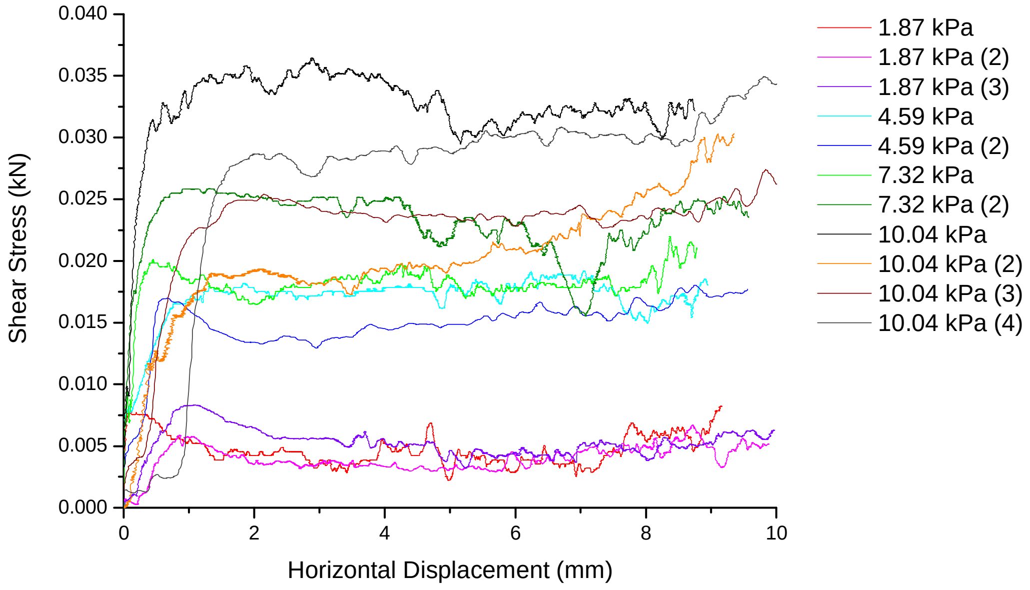
It is recommended that future centrifuge modelling of hillslope debris flow initiation should be carried out within a sealed environmental chamber in which varying intensities and durations of rainfall can be applied to the soil surface via atomising mist nozzles located above the model slope (Take, 2003; Hudacsek & Bransby, 2008). Scaling laws dictate that long periods of time can be modelled in the centrifuge. Consequently, using an environmental chamber it would be possible to investigate the effects of varying patterns of antecedent rainfall and different lengths of time between the culmination of antecedent rainfall and the commencement of high magnitude, debris flow generating rainstorms on the vulnerability of a soil slope to failure. Hot air can also be introduced into the chamber to simulate dry periods. The affects of long duration, low intensity frontal rainstorms on pore pressure development in soil slopes could also be investigated. This would have particular relevance to coarse *slightly silty* to *silty sand* soils which may be more susceptible to debris flow generation during such storms. As well as the interaction between antecedent rainfall and rainstorms of varying magnitudes, hillslope debris flow tests in an environmental chamber would also allow for the investigation of slope failure triggered during high intensity rainstorms as a result of a loss of suction at a shallow depth in the soil mantle caused by the ingress of a wetting front (Fourie, 1996; Springman *et al*. 2003; Wheeler *et al*. 2003) and in particular the antecedent and triggering conditions that contrive to generate these types of landslides. Centrifuge tests in an environmental chamber could also be used to investigate the influence of strata with varying soil properties on susceptibility to debris flow in anisotropic soils, in particular quantifying the influence of organic upper horizons on the infiltration rate and thus the susceptibility to debris flow.

A data set from such a programme of physical modelling in a centrifuge would have direct applicability in assisting the prediction of rain induced debris flow activity potentially providing threshold levels associated with endurance of soil moisture and infiltration rates in soils with varying coarsenesses. These could then be used along with generalised or measured stability parameters (frictional strength, apparent cohesion, density and mantle thickness above probable failure plane) to carry out GIS based probabilistic forecasting of debris flow generation using two dimensional infinite slope analysis, likely antecedent moisture conditions (extrapolated from measured rainfall and the hydraulic transmissivity of the soil) and likely infiltration during forecast storms (Huabin *et al*. 2005; Schmidt *et al*. 2008).

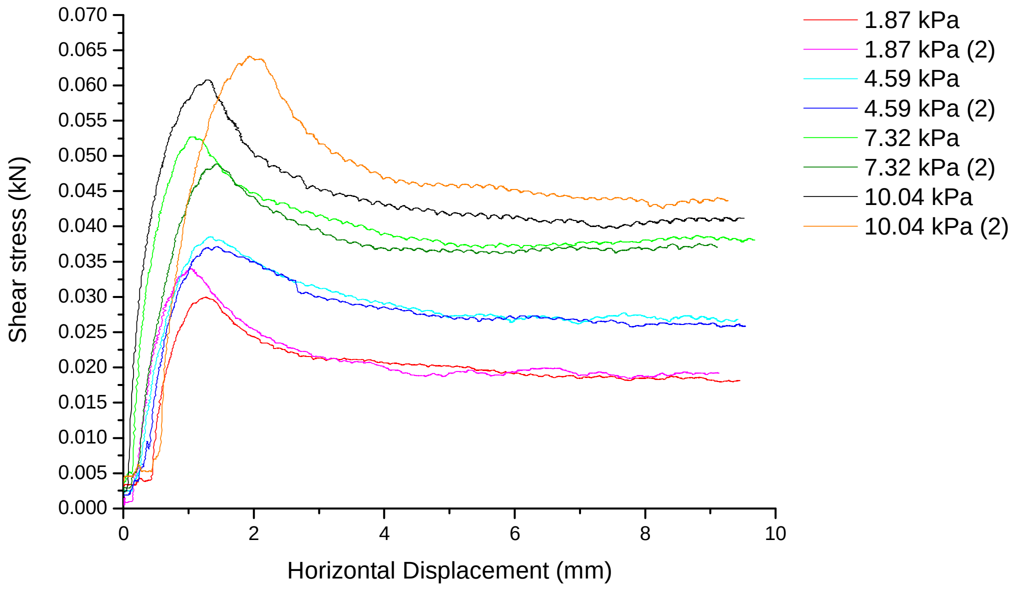
Appendix A

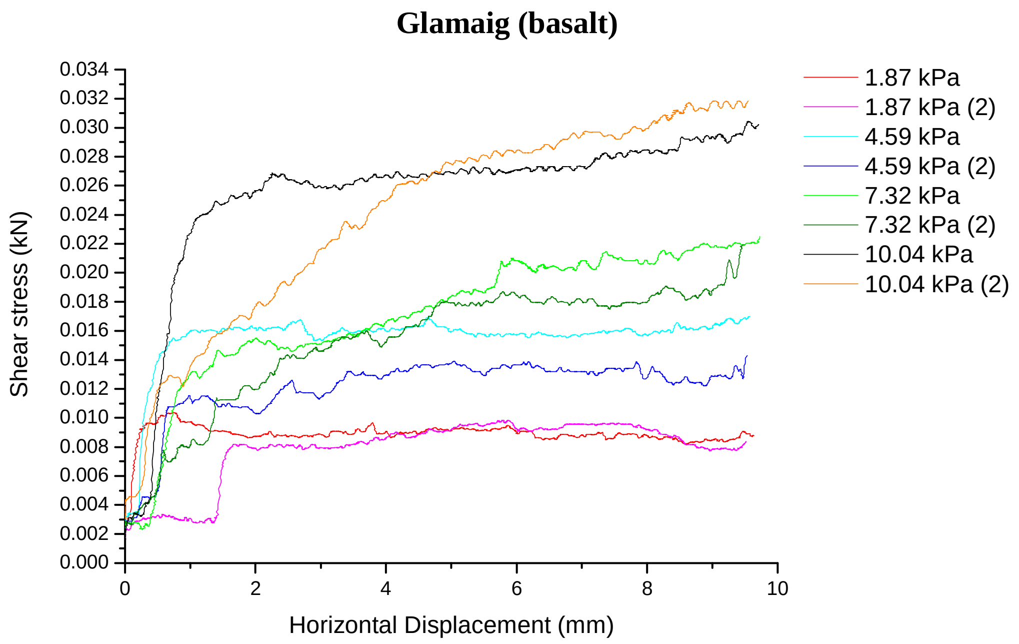
Shear Box Test Stress-Displacement Graphs

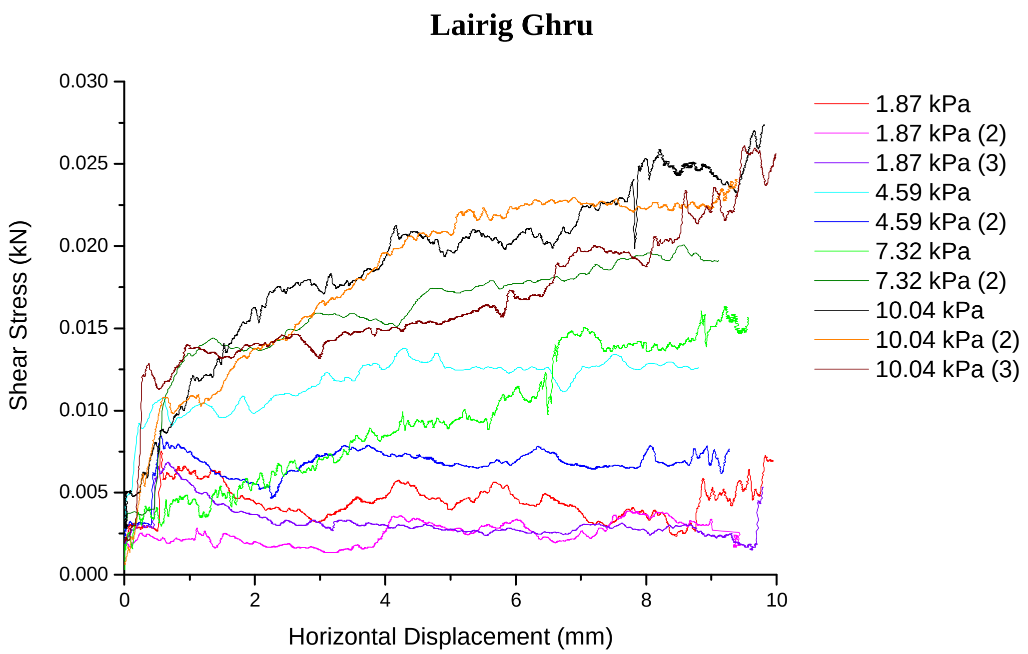
An Teallach 1

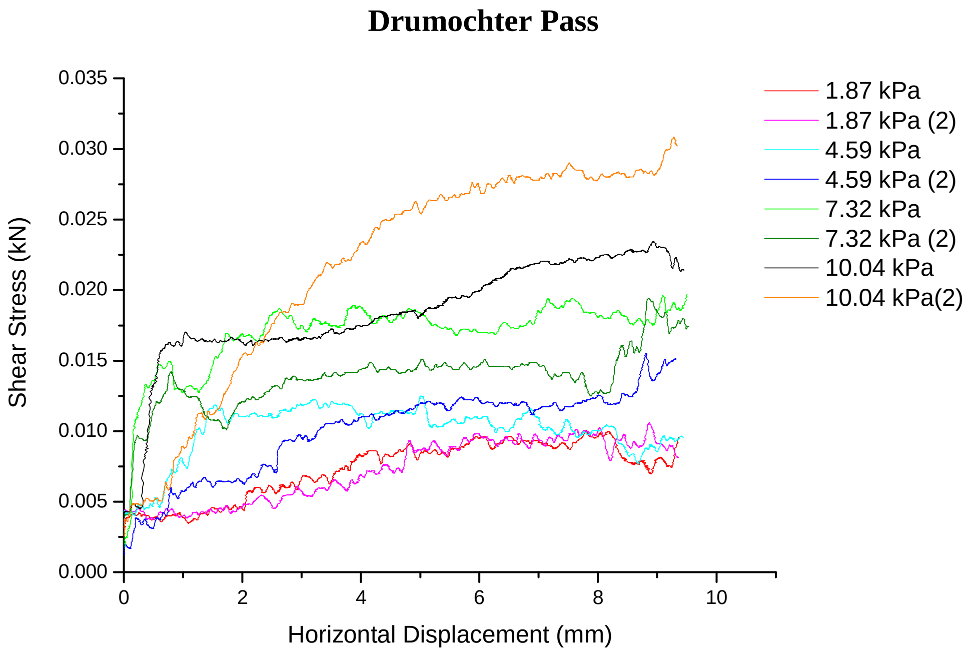


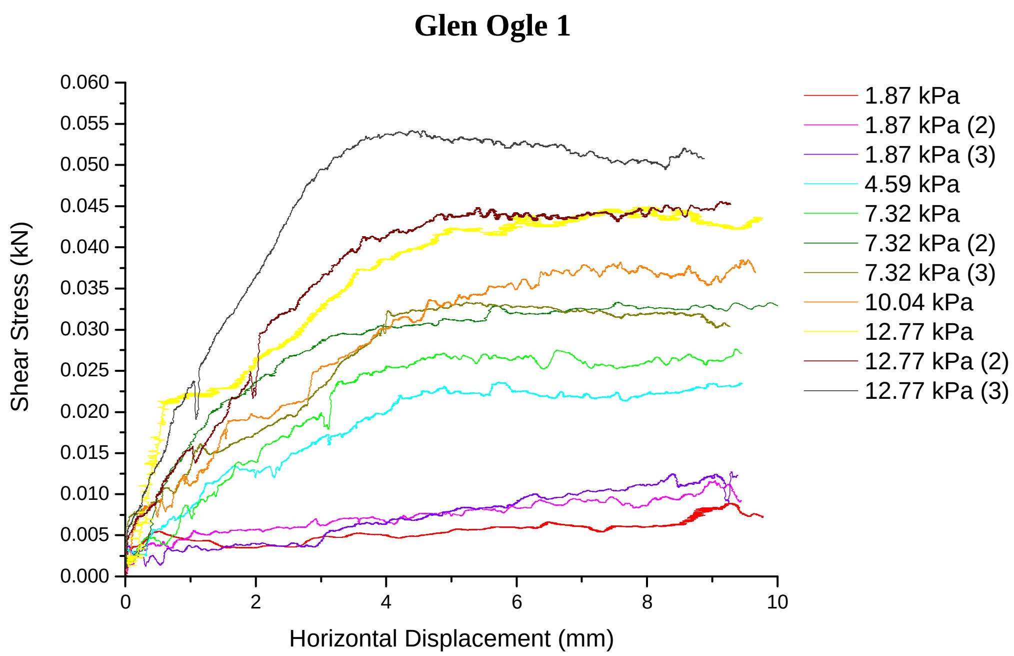
Glamaig (granite)

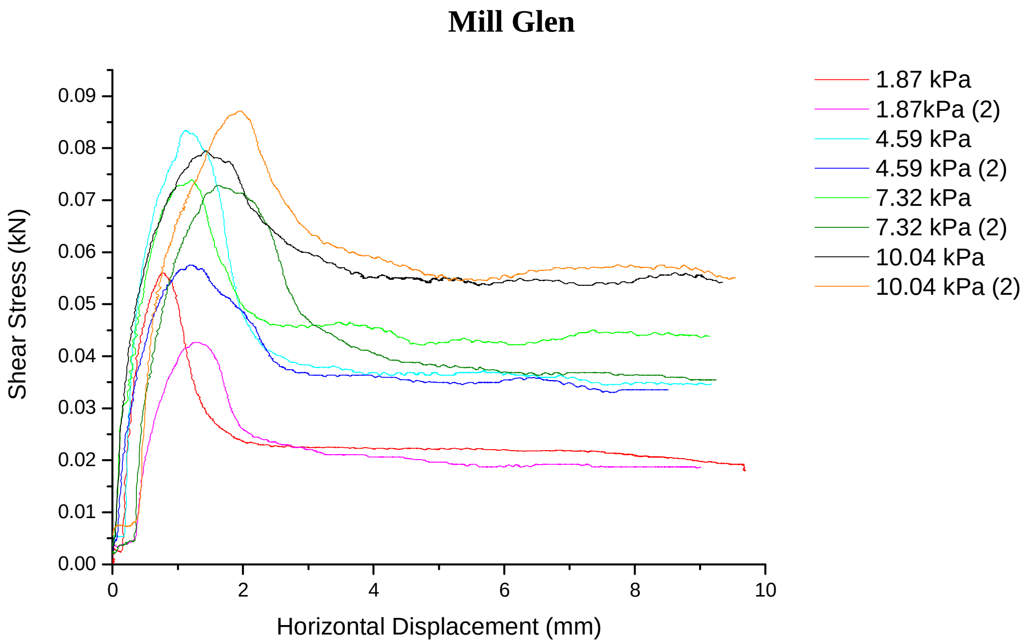



Glamaig (basalt)
Shear stress (kN)
0.034
0.032
0.030
0.028
0.026
0.024
0.022
0.020
0.018
0.016
0.014
0.012
0.010
0.008
0.006
0.004
0.002
0.000
0
2
4
6
8
10
Horizontal Displacement (mm)
1.87 kPa
1.87 kPa (2)
4.59 kPa
4.59 kPa (2)
7.32 kPa
7.32 kPa (2)
10.04 kPa
10.04 kPa (2)


Lairig Ghru
Shear Stress (kN)
0.030
0.025
0.020
0.015
0.010
0.005
0.000
0
2
4
6
8
10
Horizontal Displacement (mm)
1.87 kPa
1.87 kPa (2)
1.87 kPa (3)
4.59 kPa
4.59 kPa (2)
7.32 kPa
7.32 kPa (2)
10.04 kPa
10.04 kPa (2)
10.04 kPa (3)


Drumochter Pass
Shear Stress (kN)
0.035
0.030
0.025
0.020
0.015
0.010
0.005
0.000
0
2
4
6
8
10
Horizontal Displacement (mm)
1.87 kPa
1.87 kPa (2)
4.59 kPa
4.59 kPa (2)
7.32 kPa
7.32 kPa (2)
10.04 kPa
10.04 kPa(2)

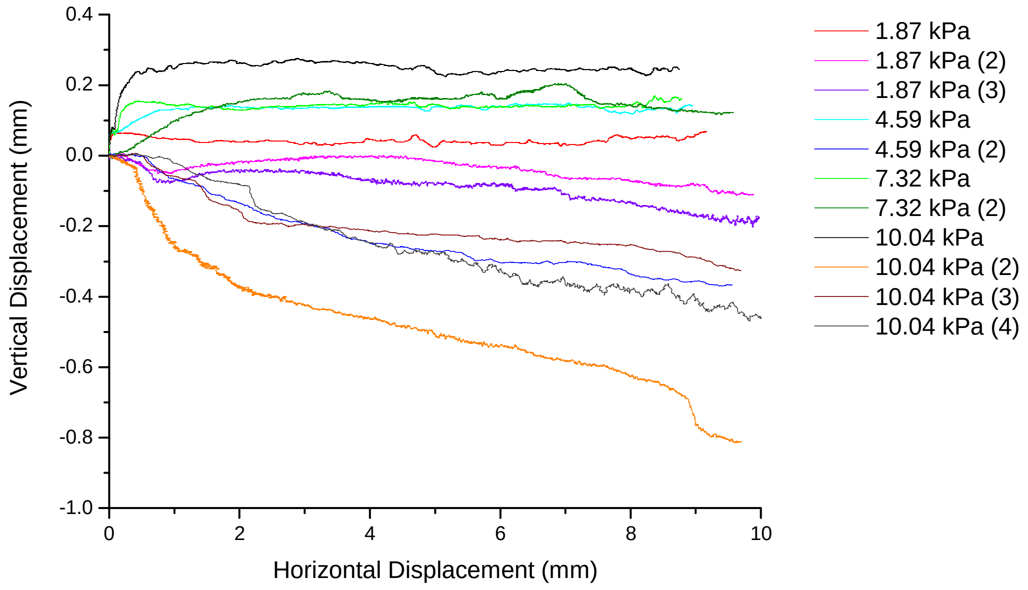

Glen Ogle 1
Shear Stress (kN)
0.060
0.055
0.050
0.045
0.040
0.035
0.030
0.025
0.020
0.015
0.010
0.005
0.000
0
2
4
6
8
10
Horizontal Displacement (mm)
1.87 kPa
1.87 kPa (2)
1.87 kPa (3)
4.59 kPa
7.32 kPa
7.32 kPa (2)
7.32 kPa (3)
10.04 kPa
12.77 kPa
12.77 kPa (2)
12.77 kPa (3)


Mill Glen
Shear Stress (kN)
0.00
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
Horizontal Displacement (mm)
0
2
4
6
8
10
1.87 kPa
1.87kPa (2)
4.59 kPa
4.59 kPa (2)
7.32 kPa
7.32 kPa (2)
10.04 kPa
10.04 kPa (2)

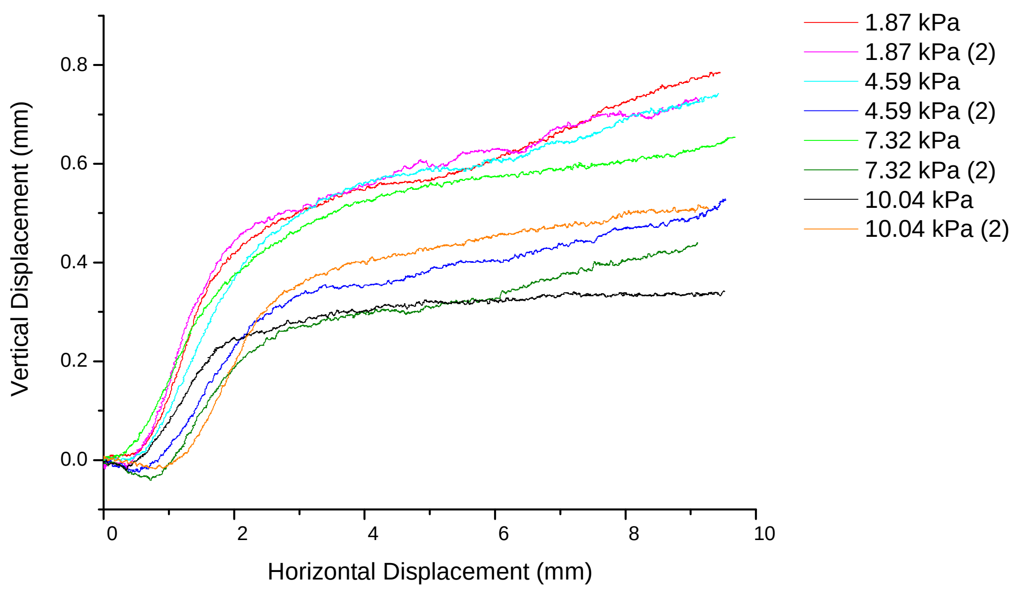
Appendix B

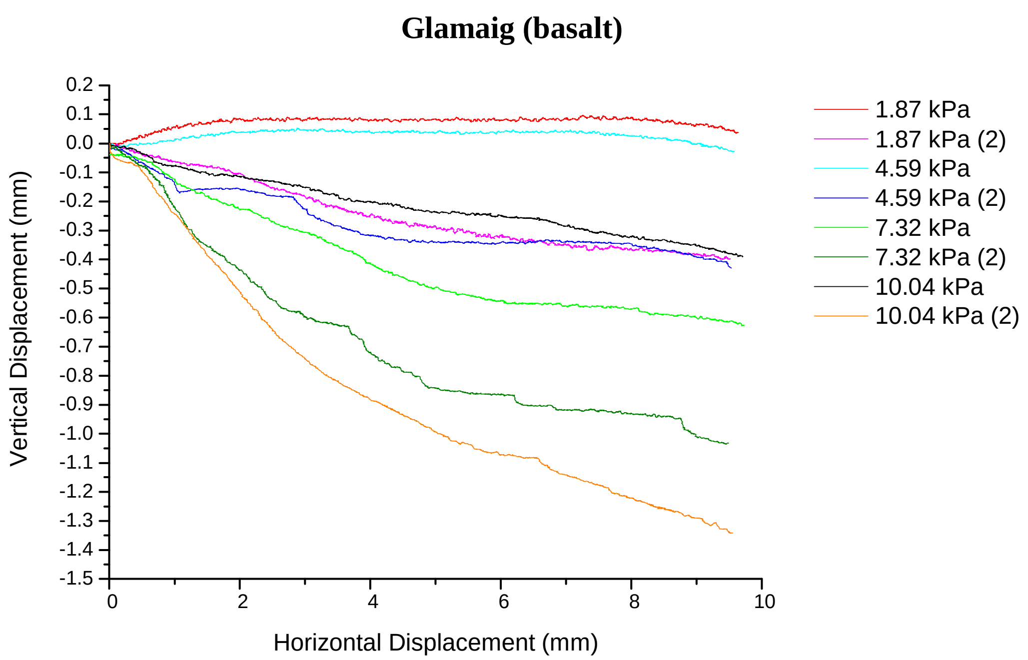
Shear Box Test Vertical Displacement Graphs

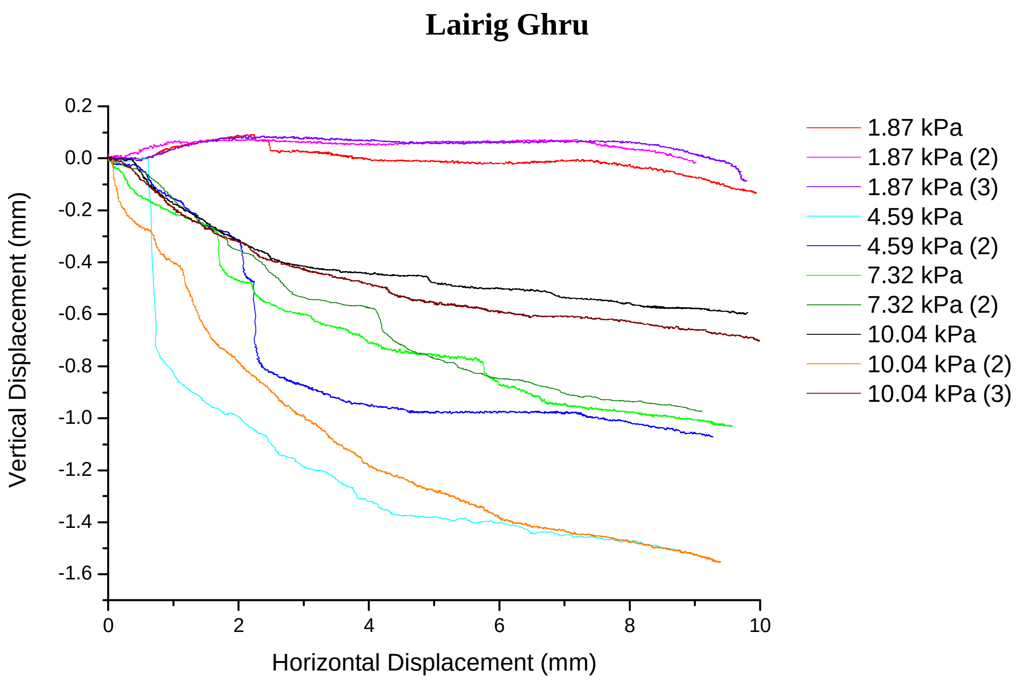
An Teallach 1

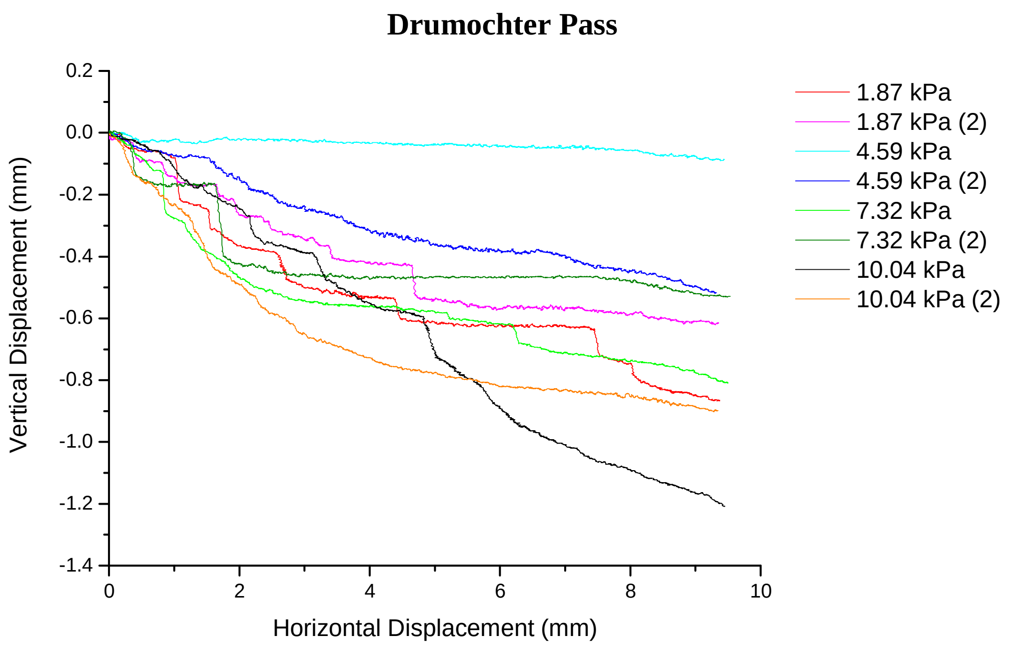


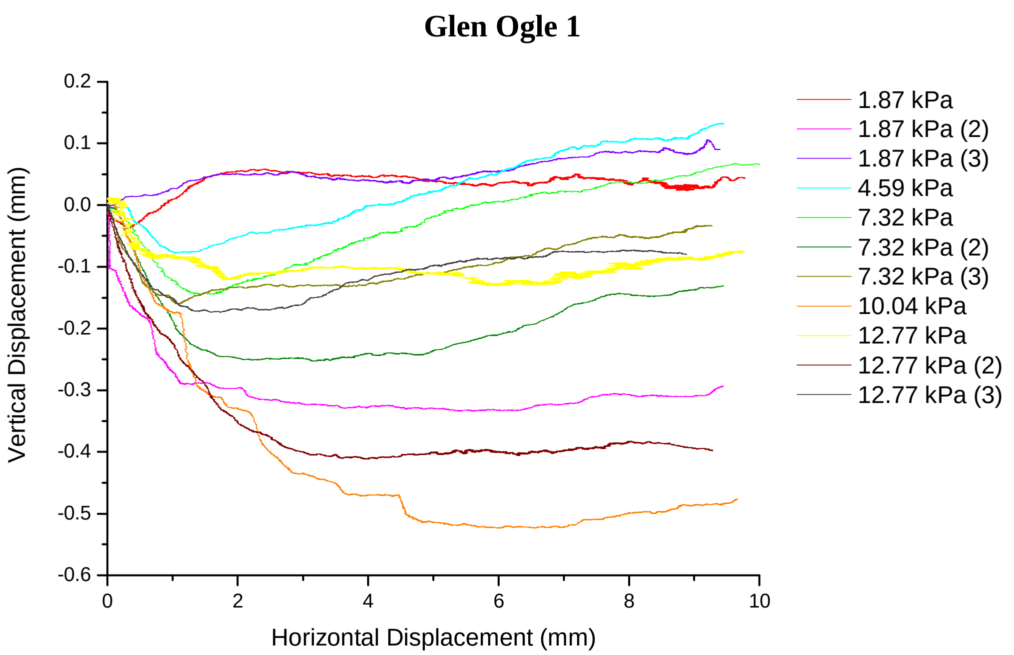
Glamaig (granite)




Glamaig (basalt)
Vertical Displacement (mm)
Horizontal Displacement (mm)
1.87 kPa
1.87 kPa (2)
4.59 kPa
4.59 kPa (2)
7.32 kPa
7.32 kPa (2)
10.04 kPa
10.04 kPa (2)


Lairig Ghru
Vertical Displacement (mm)
Horizontal Displacement (mm)
1.87 kPa
1.87 kPa (2)
1.87 kPa (3)
4.59 kPa
4.59 kPa (2)
7.32 kPa
7.32 kPa (2)
10.04 kPa
10.04 kPa (2)
10.04 kPa (3)


Drumochter Pass
Vertical Displacement (mm)
Horizontal Displacement (mm)
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
-1.2
-1.4
0
2
4
6
8
10
1.87 kPa
1.87 kPa (2)
4.59 kPa
4.59 kPa (2)
7.32 kPa
7.32 kPa (2)
10.04 kPa
10.04 kPa (2)


Glen Ogle 1
Vertical Displacement (mm)
Horizontal Displacement (mm)
0.2
0.1
0.0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
0
2
4
6
8
10
1.87 kPa
1.87 kPa (2)
1.87 kPa (3)
4.59 kPa
7.32 kPa
7.32 kPa (2)
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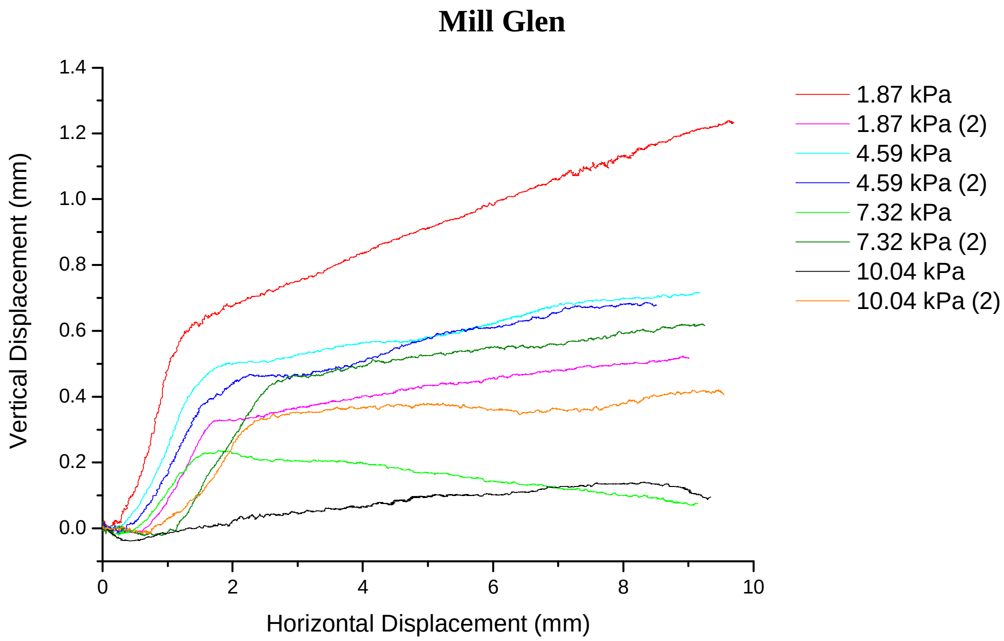
10.04 kPa
12.77 kPa
12.77 kPa (2)
12.77 kPa (3)



Mill Glen
Vertical Displacement (mm)
Horizontal Displacement (mm)
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
2
4
6
8
10
1.87 kPa
1.87 kPa (2)
4.59 kPa
4.59 kPa (2)
7.32 kPa
7.32 kPa (2)
10.04 kPa
10.04 kPa (2)

Appendix C

Infinite Slope Analysis Equation

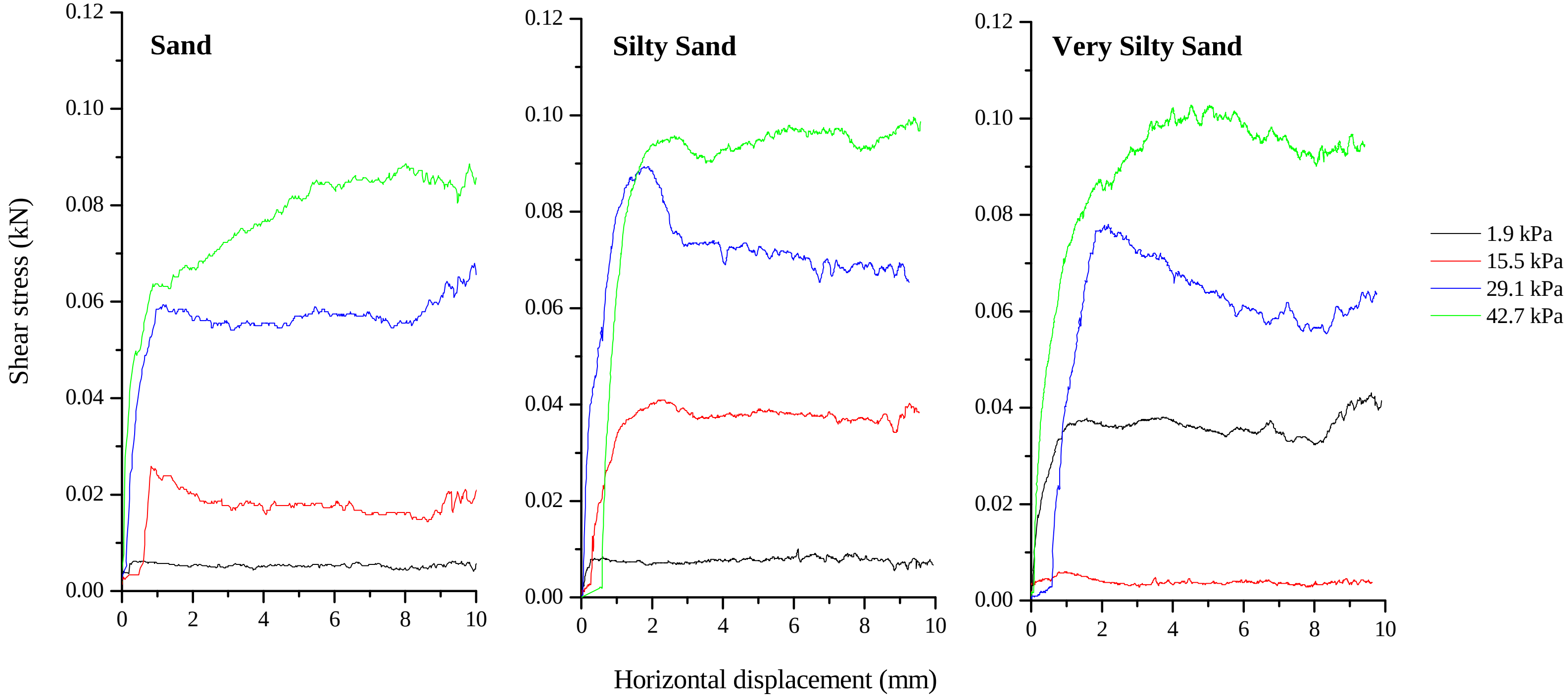
Infinite slope analysis in this research was carried out using the following equation:

$$F_s = \frac{c' + (\gamma.z - \gamma_w.h).\cos^2\beta.\tan\phi'}{\gamma.z.\sin\beta.\cos\beta.}$$

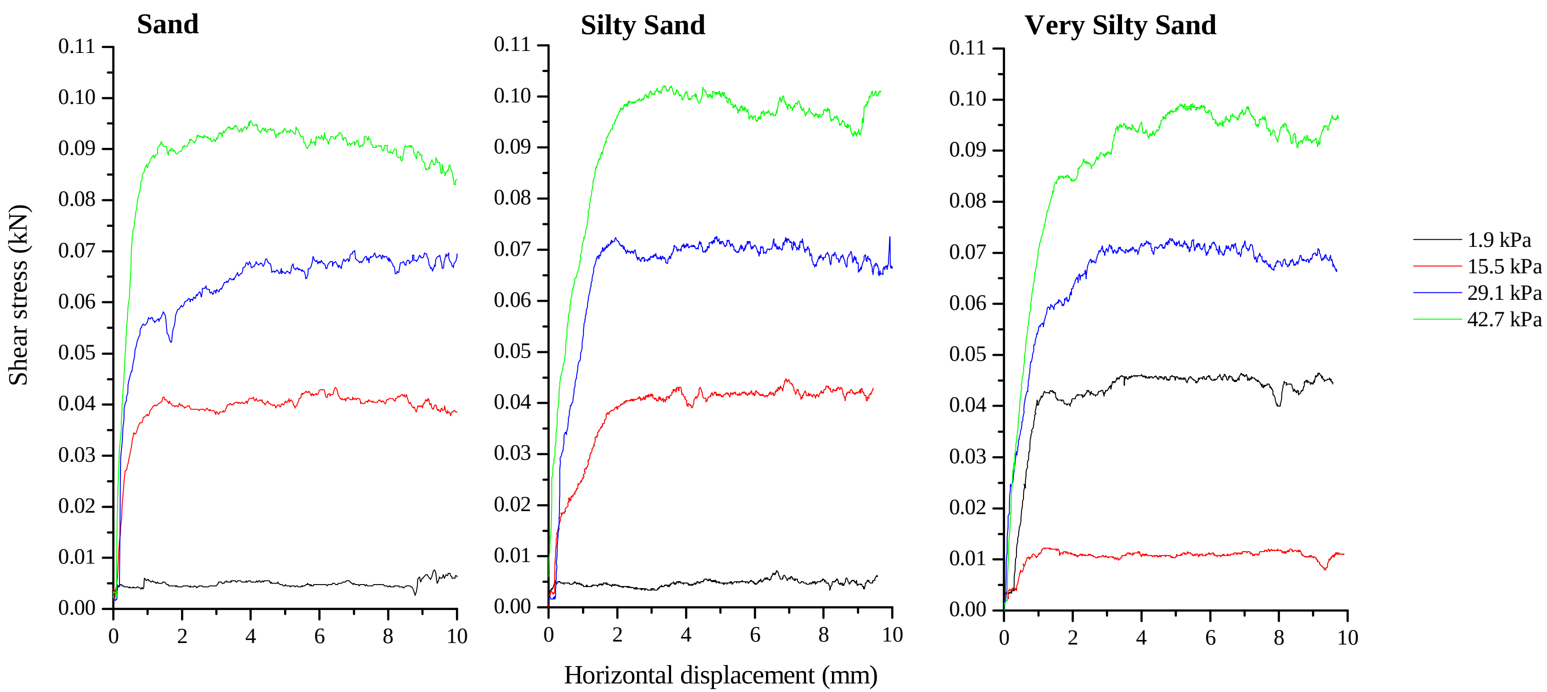
Where Fs = Factor of Safety, c' = cohesion (kPa), γ = unit weight of soil (kN m^{-3}), z = height of profile above slip plane (m), γ_w = unit weight of water (kN m^{-3}), h = height of water table (m), β = slope gradient (degrees), φ' = internal angle of friction (degrees).

Appendix D

Centrifuge soil shear box stress-displacement graphs



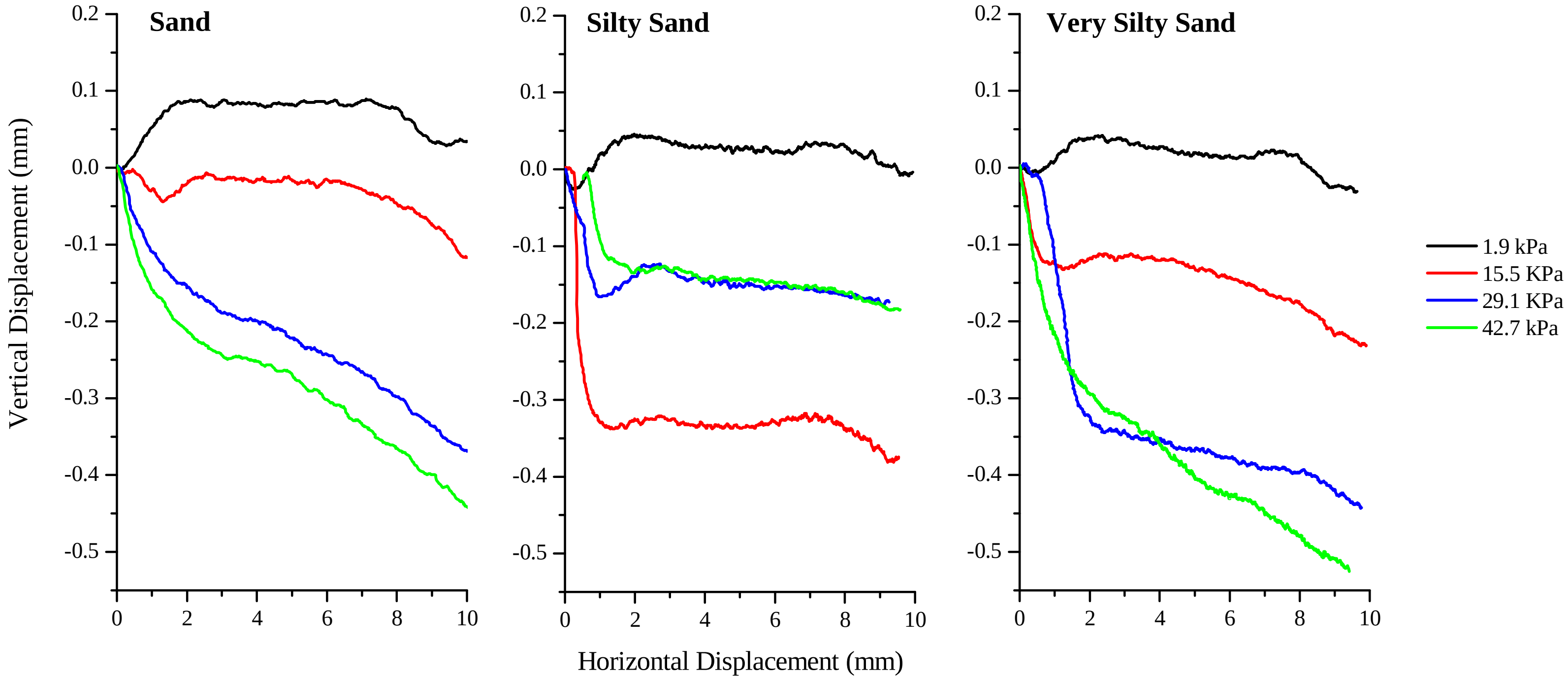
A: Centrifuge soil shear stress



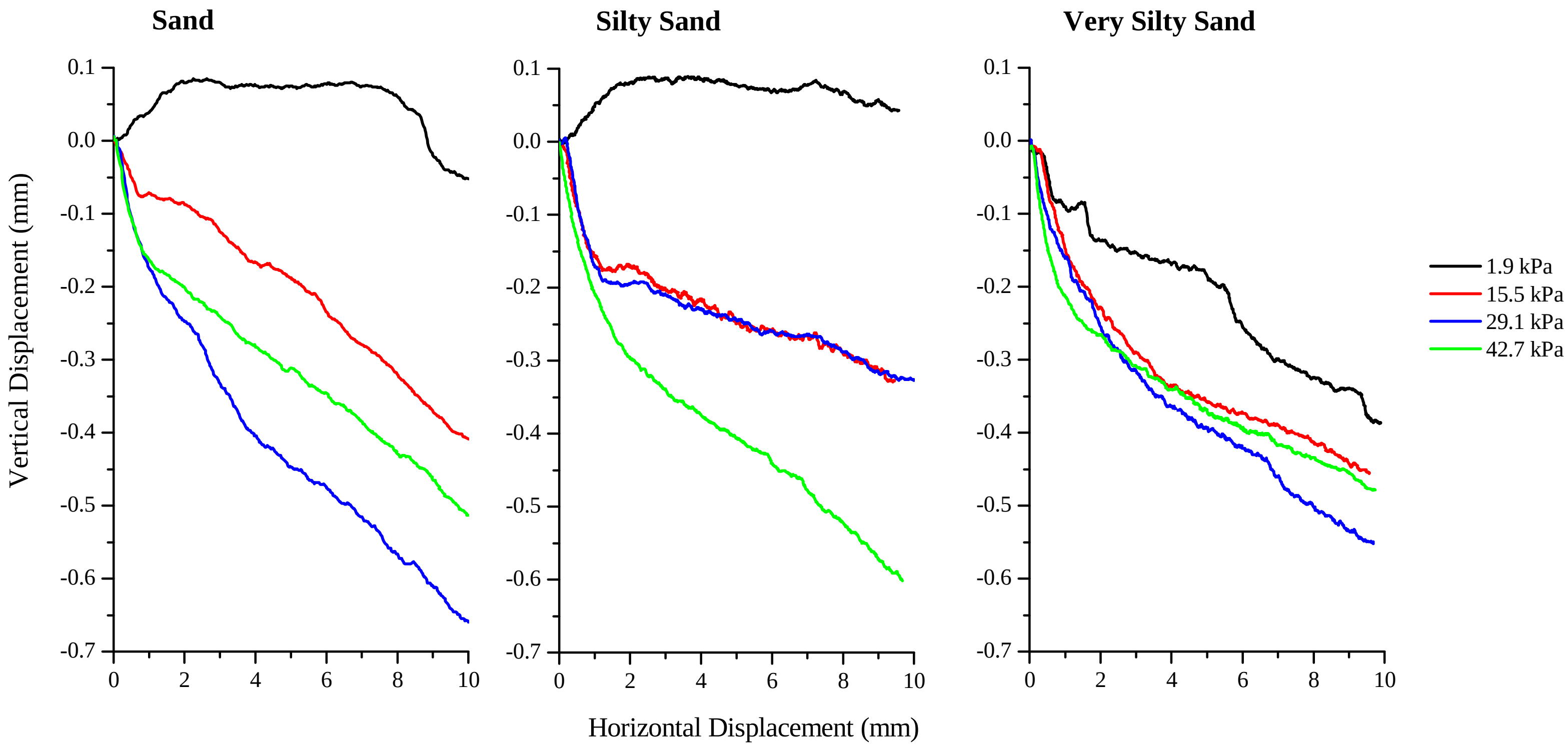
B: Centrifuge soil – cemented “bedrock” slope interface shear stress

Appendix E

Shear Box Test Vertical Displacement Graphs



A: Centrifuge soil vertical displacement



B: Centrifuge soil – cemented "bedrock" slope vertical displacement

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